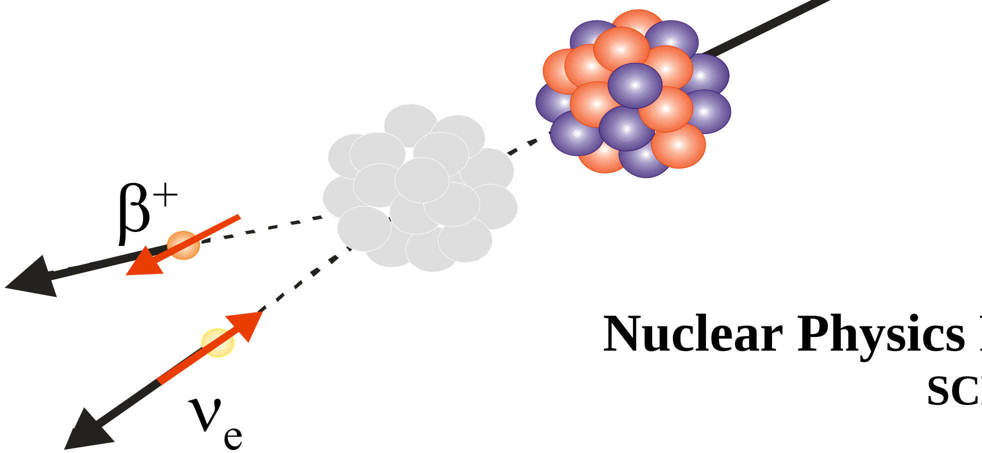
Low energy weak interaction studies using β-decay of radioactive nuclei



Nuclear Physics Research at the MYRRHA accelerator

SCK-CEN, Mol, April 06-09, 2008

Nathal Severijns

Kath. University Leuven, Belgium

Nuclei of interest

- nuclei at or close to the **N = Z line**

    - nuclei with **$0^+ \rightarrow 0^+$ transitions**

    - **T = 1/2 mirror nuclei** (N = Z-1 → N = Z+1; e.g. $^{21}Na \rightarrow {}^{21}Ne$)

- nuclei with **fast** (small log*ft*) and pure **Gamow-Teller transitions**

1. $Ft^{0^+ \rightarrow 0^+}$

- CVC
- unitarity of CKM matrix
- right-handed currents
- scalar currents

2. searches for exotic weak currents

- scalar currents
- tensor currents

3. symmetry tests

- parity
- time reversal

N. Severijns et al., Rev. Mod. Phys. 78 (2006) 991

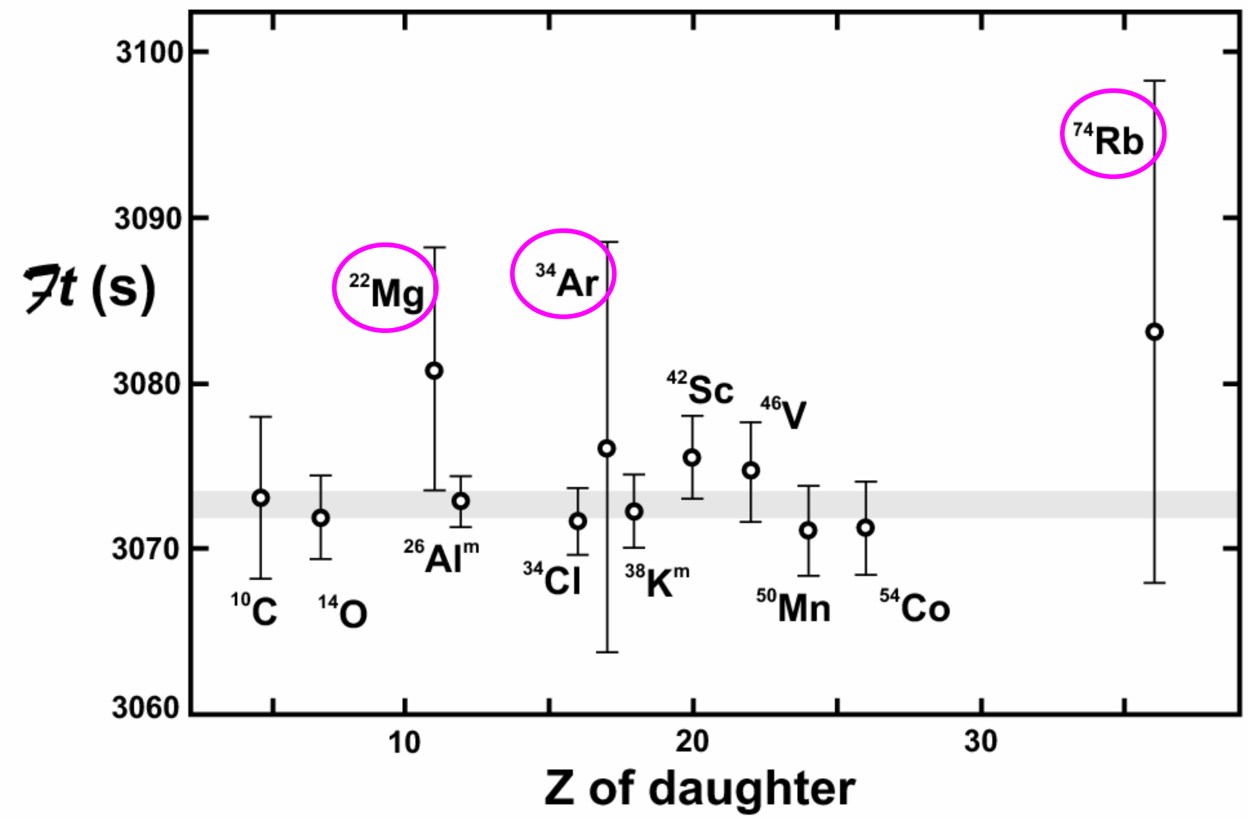
4. searches for heavy neutrinos

1. $\mathfrak{F}t$-values of $0^+ \rightarrow 0^+$ superallowed Fermi transitions

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \mathbf{3074.4(12)\ s} \quad (^{1,2})$$

ft ↓ Q_{EC}, $t_{1/2}$ and BR

δ_R', $\delta_{NS} - \delta_C$, Δ_R^V → theory



1. test of CVC hypothesis

→ OK @ 4×10^{-4} level

2. test of unitarity of CKM-matrix

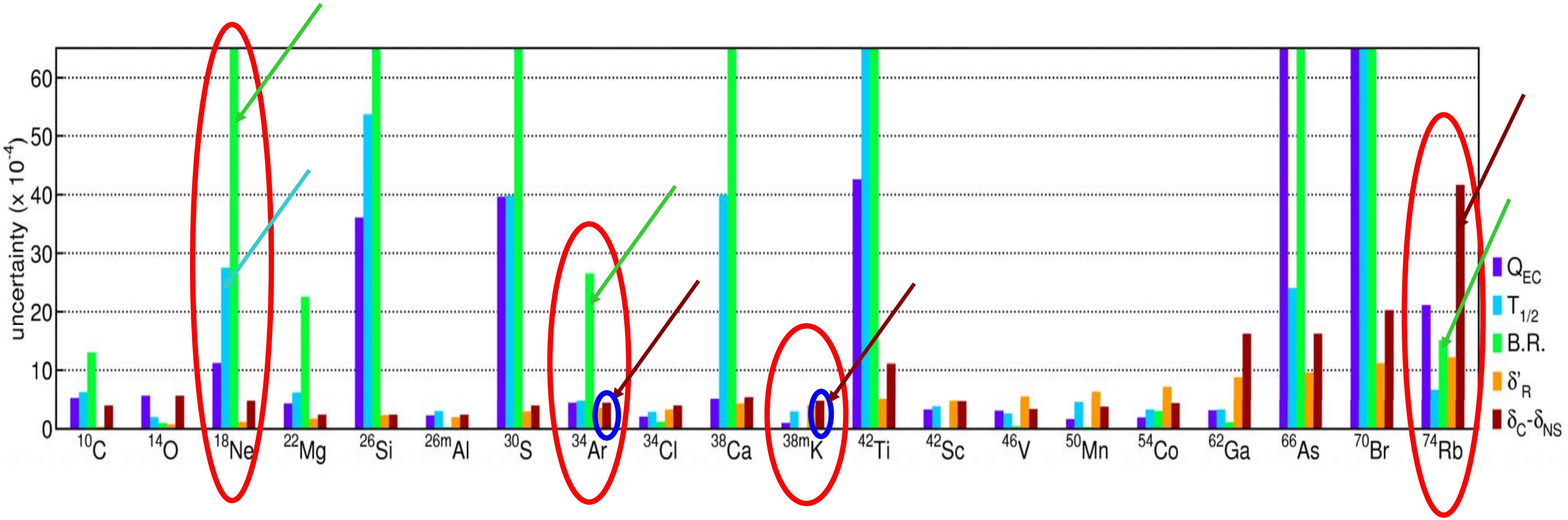
$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = \mathbf{0.9987(11)}$$

(with new values for V_{us})

(^{1}) Towner and Hardy, PRL 94 (2003) 092501, PR C71 (2005) 055501
(^{2}) Savard et al., PRL 95 (2005) 102501

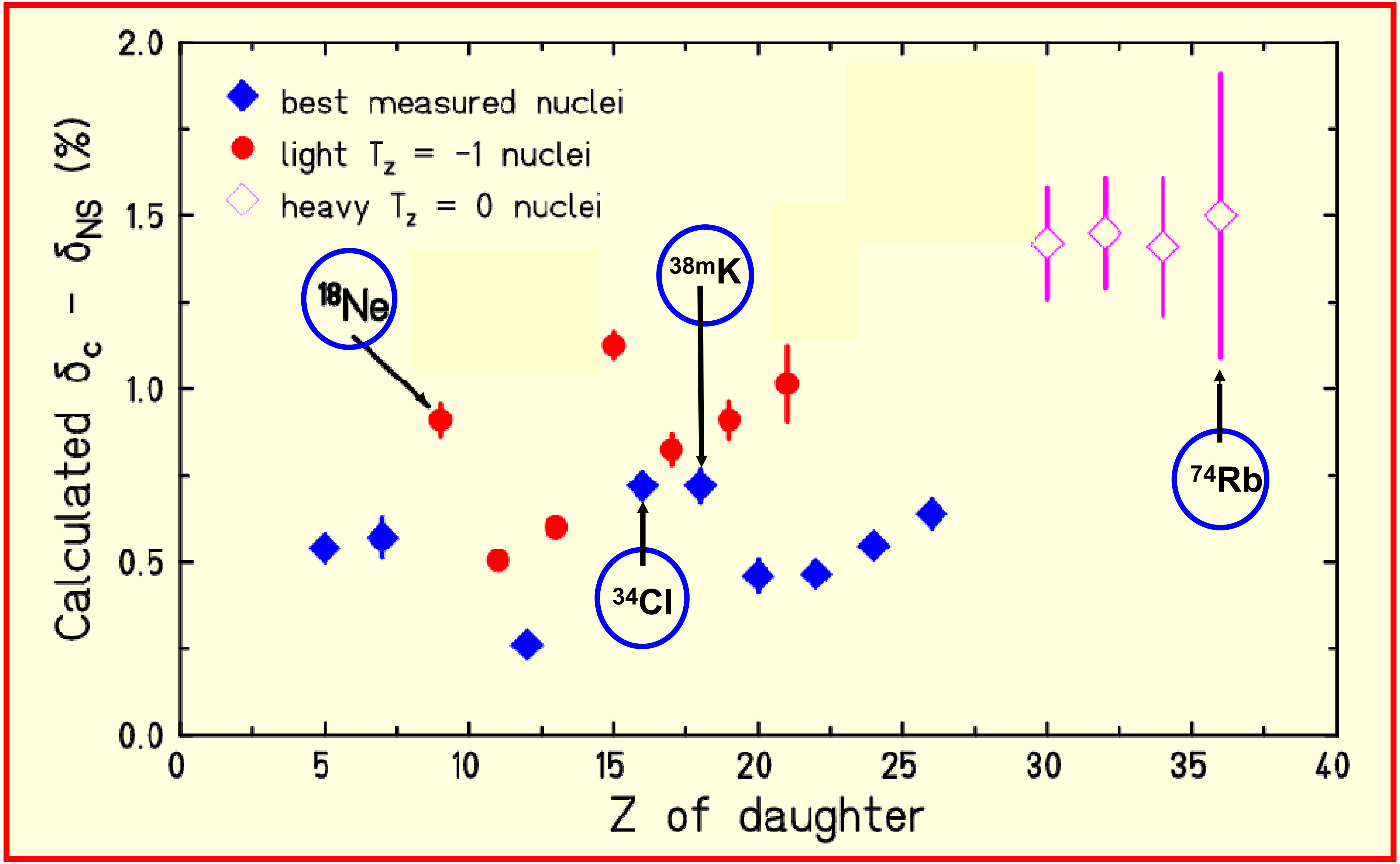
Error budget, required precision, and opportunities for MYRRHA (arrows)

- **overall precision: Ft = (3074.4 ± 1.2) s**
  $\Rightarrow$ **4 * 10^{-4}**
  $\Rightarrow$ **single measurements of $T_{1/2}$ and BR : < 10^{-3}**
- **theoretical corrections: δ_C, δ'_R ~ 1% → < 10%**



Options: - improve quantities indicated by green & blue arrows
- if CVC accepted → Ft-measurements test δ_c - δ_{NS} from theoretical models
- go for factor ~10 higher precision in Ft than available now for the 4 isotopes indicated

isospin-mixing corrections + NS radiative corrections



Towner & Hardy, 2005

physics information from the $0^+ \rightarrow 0^+$ Fermi transitions

1. **Conserved Vector Current hypothesis**

   cf. supra

2. **unitarity of CKM quark-mixing matrix**

   cf. supra

3. **right-handed (V+A) currents**

   $-0.0005 < \zeta < 0.0015$ (90% C.L.)

4. **scalar currents**

$$-0.005 < \mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) < 0.011$$

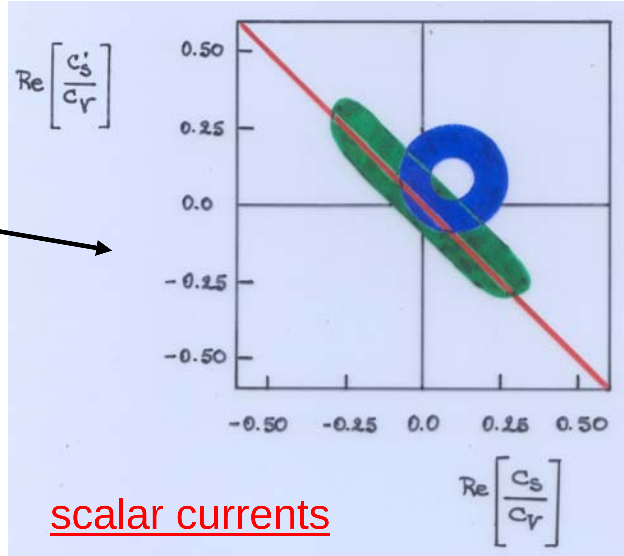
(90% CL)

Left Right Symmetric models

$W_1 = W_L \cos\zeta - W_R \sin\zeta$

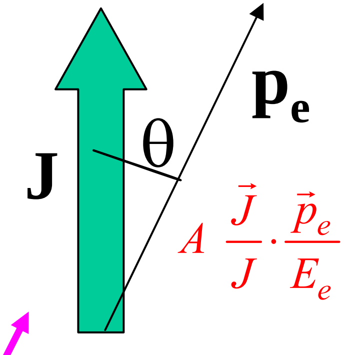
$W_2 = W_L \sin\zeta + W_R \cos\zeta$

$\delta = m_1^2 / m_2^2$



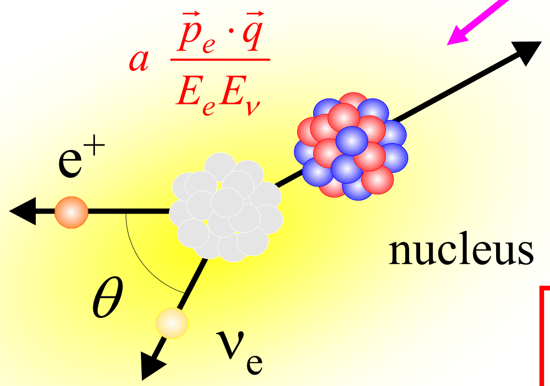
2. Searches for exotic weak currents via correlation measurements

decay rate for **beta decay**
of **(un)polarized nuclei :**



$$\omega(E,\,\Omega,\,\ldots)\;\propto\;\xi\left\{1+a\,\frac{\vec{p}_e\cdot\vec{q}}{E_eE_\nu}+b\,\frac{\gamma m_e}{E_e}+A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}+R\,\vec{\sigma}\cdot\frac{\vec{J}}{J}\times\frac{\vec{p}_e}{E_e}+\ldots\right\}$$

β-ν correlation	Fierz interference term (b ≡ 0 in standard model)	β-asymmetry	R-correlation



$$\tilde{X}=\frac{X}{1+b\,\frac{\gamma m_e}{E_e}}\qquad (X = a,\,A,\,\ldots)\quad \gamma=\sqrt{1-(\alpha Z)^2}$$

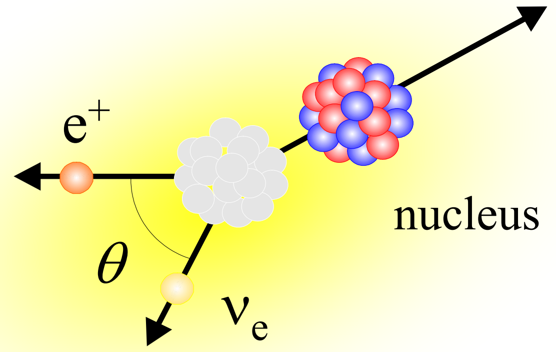
Note: ***a, b, A, R***, … depend on the coupling strengths for the different possible weak interaction types (i.e A, V, S, T)

J,D, Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

2a. βν-correlation, *a*

measure $a\,\dfrac{\vec{p}_e\cdot\vec{q}}{E_eE_\nu}$ or $\tilde{a} = \dfrac{a}{1 + b\,\dfrac{\gamma m_e}{E_e}}$

(with $\gamma = \sqrt{1-(\alpha Z)^2}$)



$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}\right]$$

$$b_F \cong Re\,\frac{C_S + C'_S}{C_V}$$

$$b_{GT} \cong Re\,\frac{C_T + C'_T}{C_A}$$

(assuming maximal P-violation and T-invariance for V and A interactions)

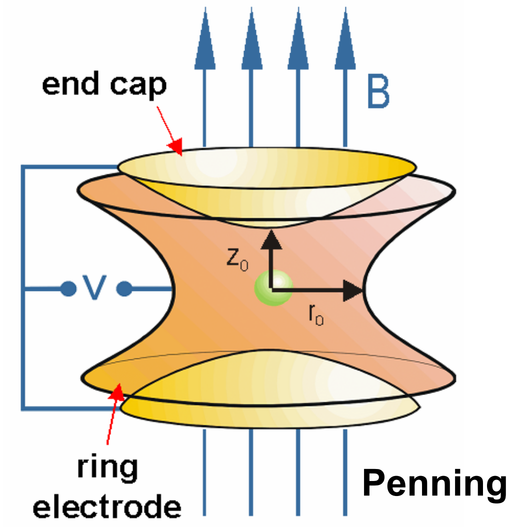
recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4}

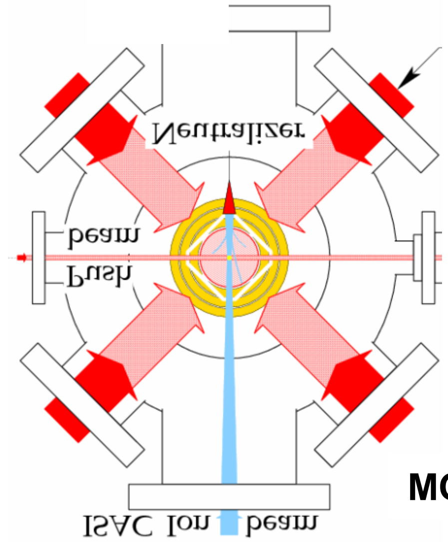
traps for correlations in nuclear beta decay

isotope	trap	meas.	lab
^{21}Na	MOT	a_F (1)	LBNL
^{38m}K	MOT	a_F (2)	TRIUMF
^{6}He	Paul	a_{GT}	LPC/GANIL
^{35}Ar	Penning	a_F	KUL/ISOLDE
^{21}Na, ^{19}Ne, ^{23}Mg	MOT	a, D	KVI
^{82}Rb	MOT	A_{GT}	LANL

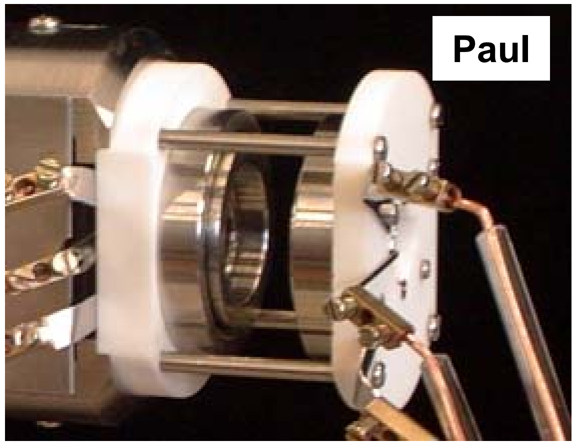
(1) = 0.5243(91) Scielzo et al. PRL 93(2004) 102501
(2) = 0.9978(30)(37) Gorelov et al. PRL 94 (2005) 142501

N. Scielzo, S.J. Freedman et al., PRL 93 (2004) 102501
A. Gorelov, J. Behr et al., PRL 94 (2005) 142501
R. Rodriguez, O. Naviliat et al., NIM A565 (2006) 876
M. Beck, N. Severijns et al., NIM A503 (2003) 567
G.P. Berg, K. Jungmann et al., NIM B204 (2003) 52
S.G. Crane, D.J. Vieira et al., PRL 86 (2001) 2967

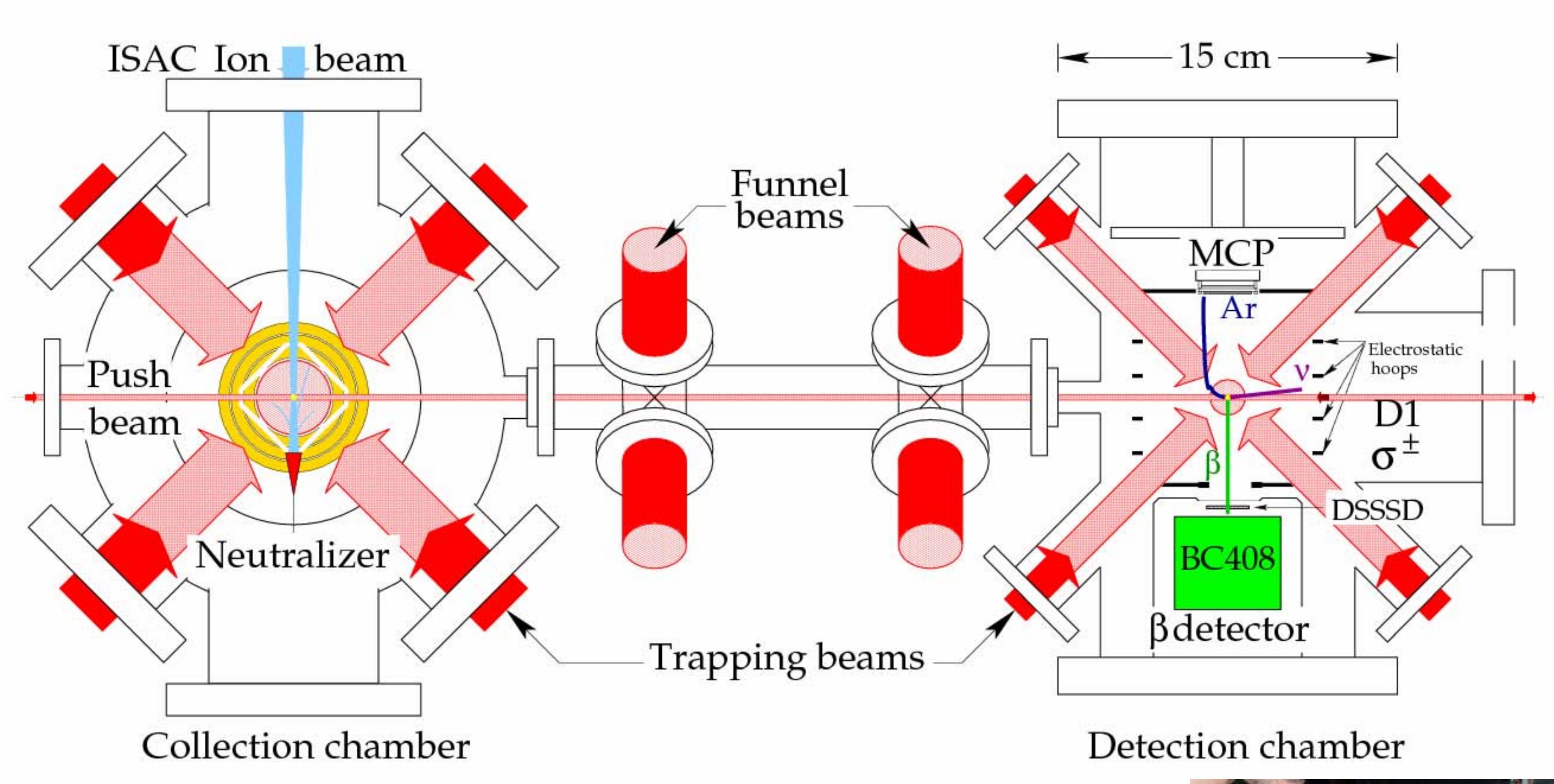


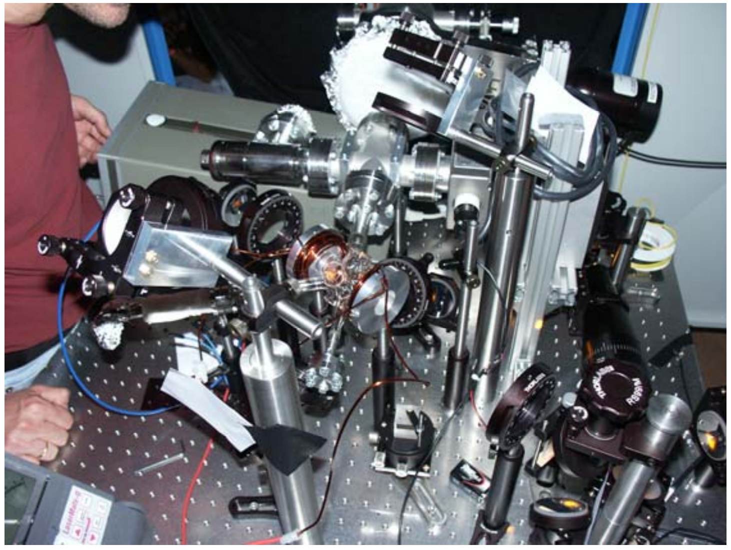


MOT



TRINAT MOT trap at TRIUMF-ISAC (Vancouver)





search for exotic scalar couplings with ^{38m}K **(J. Behr et al.)**

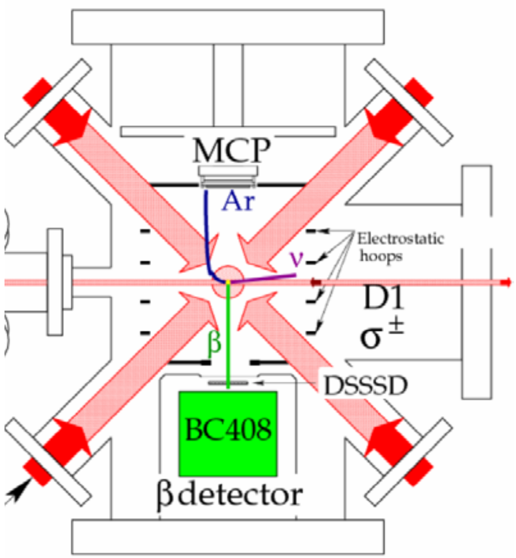
$$^{38m}\mathrm{K} \rightarrow {}^{38}\mathrm{Ar} + e^{+} + \nu$$

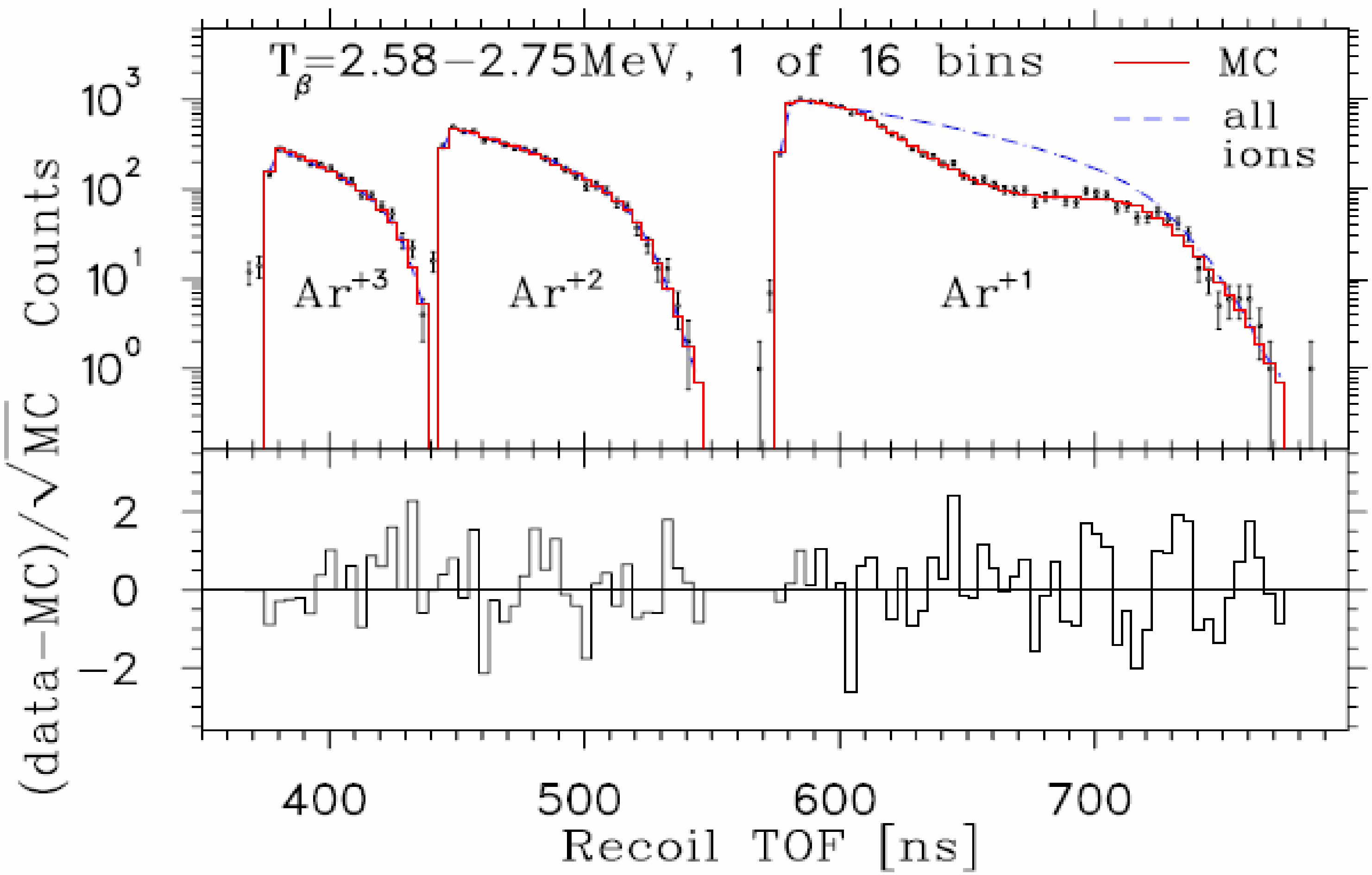
superallowed $0^+ \rightarrow 0^+$ pure Fermi transition ($t_{1/2}$ = 0.95 s)

$$\tilde{a} = \frac{a}{1+\gamma \frac{m_e}{E_e} b} = 0.9981 \pm 0.0030 \pm 0.0035 \qquad \Rightarrow \qquad \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2} \leq 0.097$$

$(\tilde{a}_{SM} = 1)$

(90% C.L. $\cong$ 1.65σ)





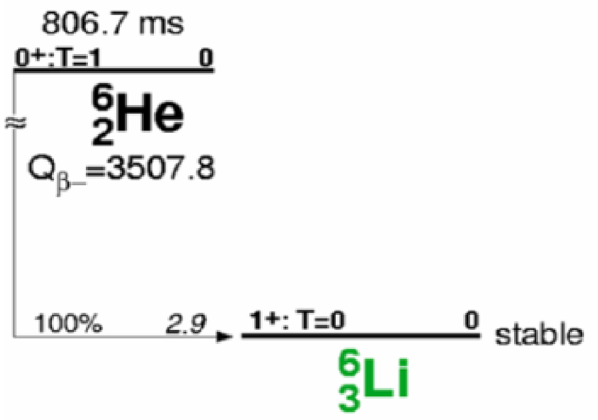
A. Gorelov, J. Behr et al., Phys. Rev. Lett. 94 (2005) 142501

LPC-Caen Paul trap at GANIL (O. Naviliat, G. Ban et al.)

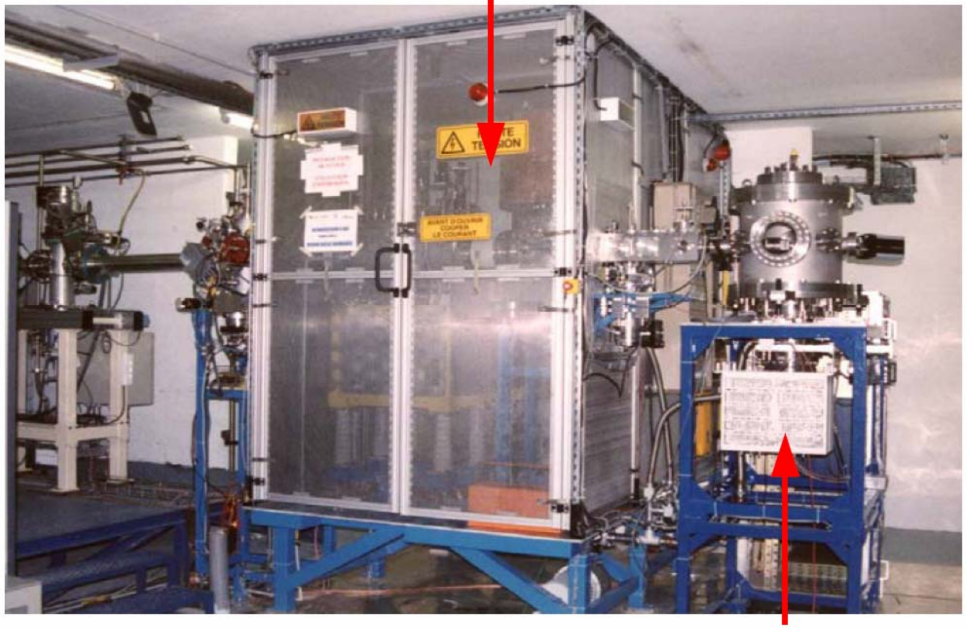
- search for exotic tensor couplings

$a\left(\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}\right)$ in a Gamow-Teller transition

$$^6\text{He} \rightarrow {}^6\text{Li} + e^- + \bar{\nu}_e$$

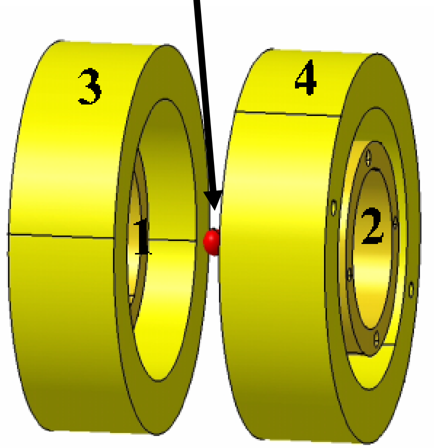


cooling /bunching



trapping/measuring

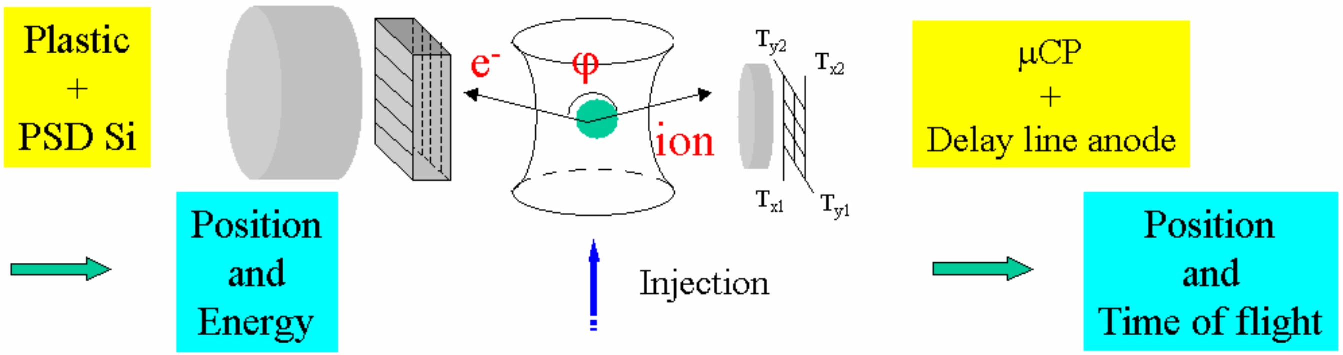
ion cloud



LPC-Caen Paul trap

β - recoil coincidences

back-to-back geometry



O. Naviliat

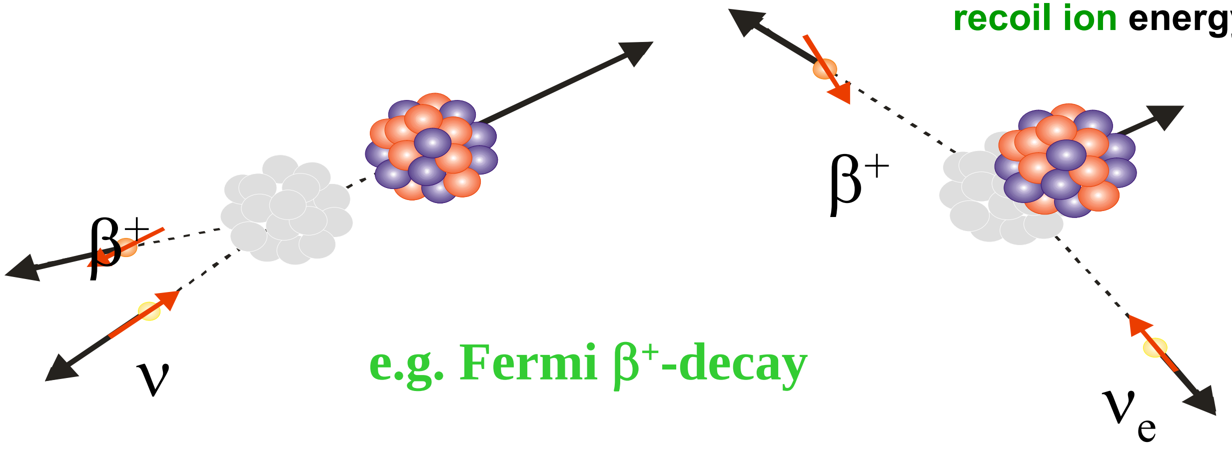
WITCH double-Penning trap system at ISOLDE-CERN

K.U.Leuven, ISOLDE-CERN, Uni Münster, GSI, NPI-Řež (Prague)

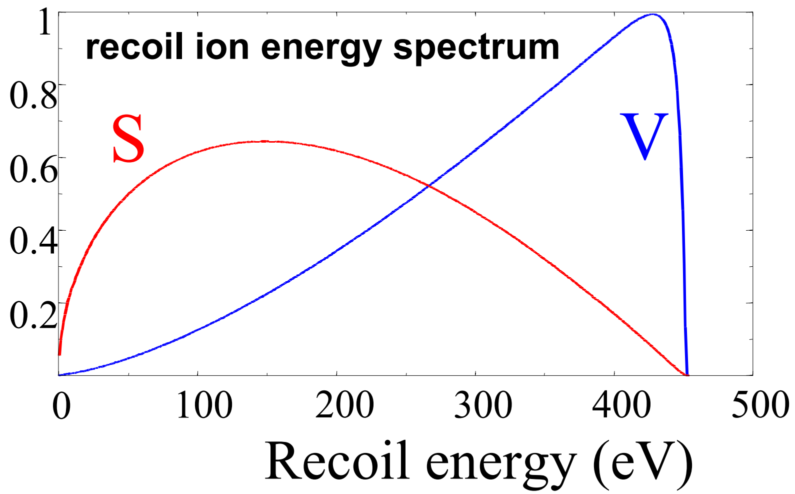
Weak Interaction Trap for CHarged particles

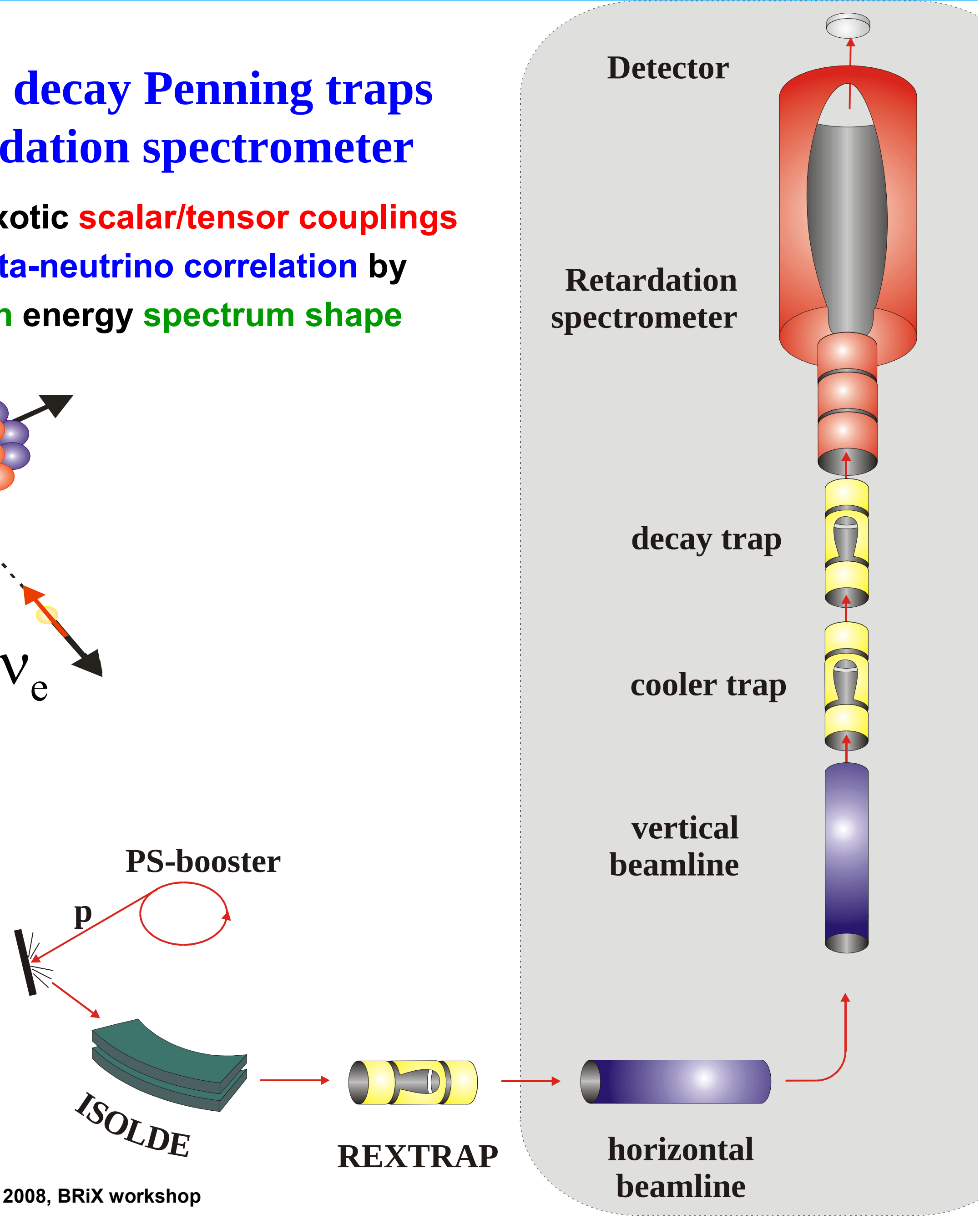
cooler & decay Penning traps + retardation spectrometer

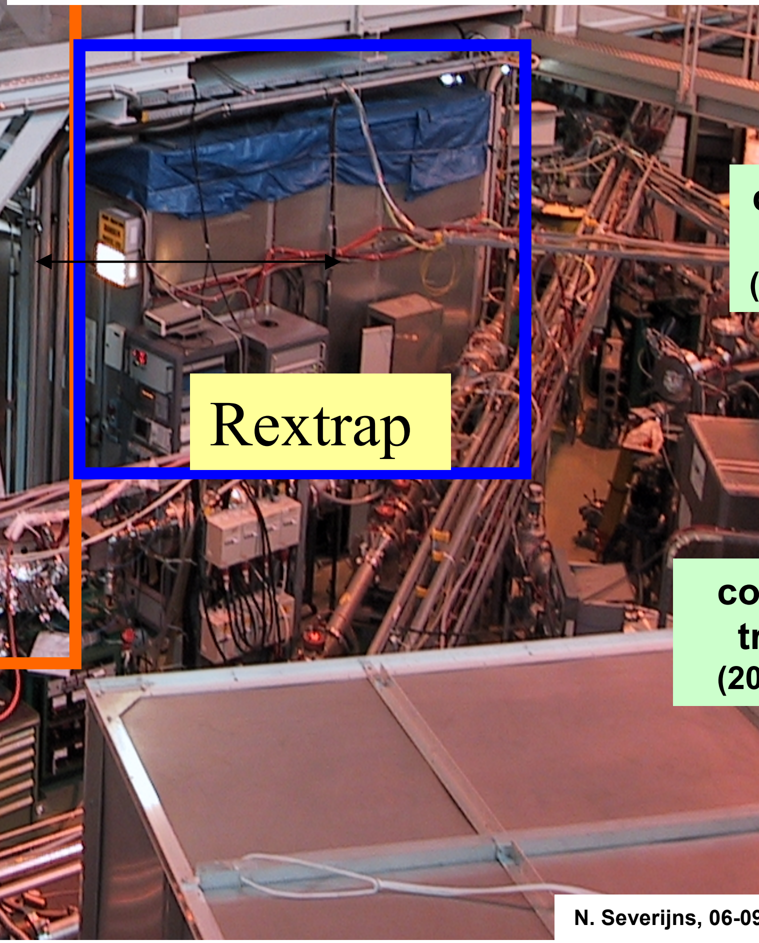
search for exotic scalar/tensor couplings
in the beta-neutrino correlation by
recoil ion energy spectrum shape

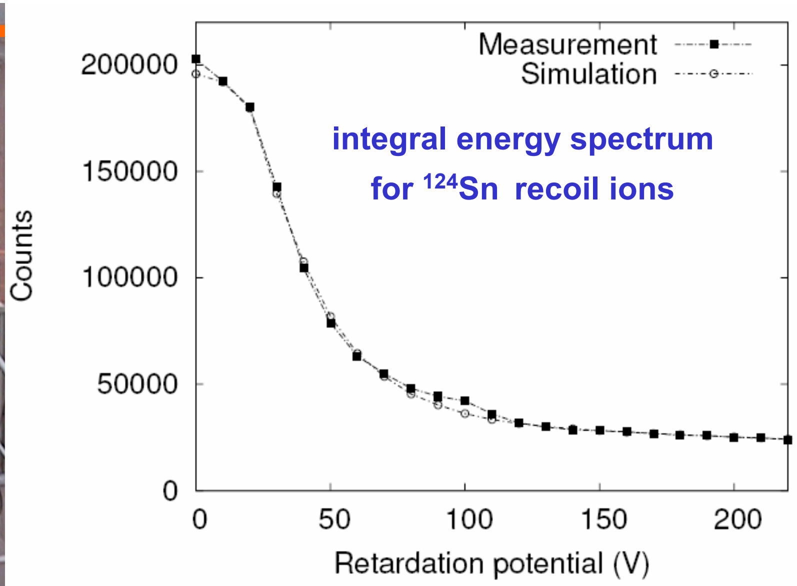


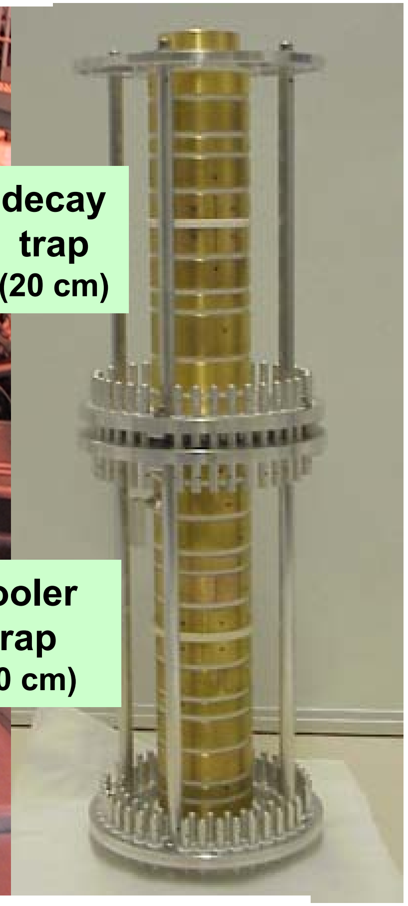
e.g. Fermi β^+-decay



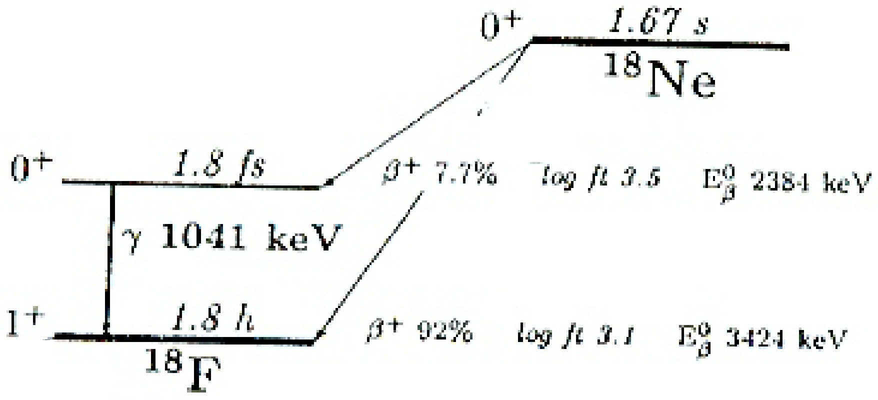




Rextrap

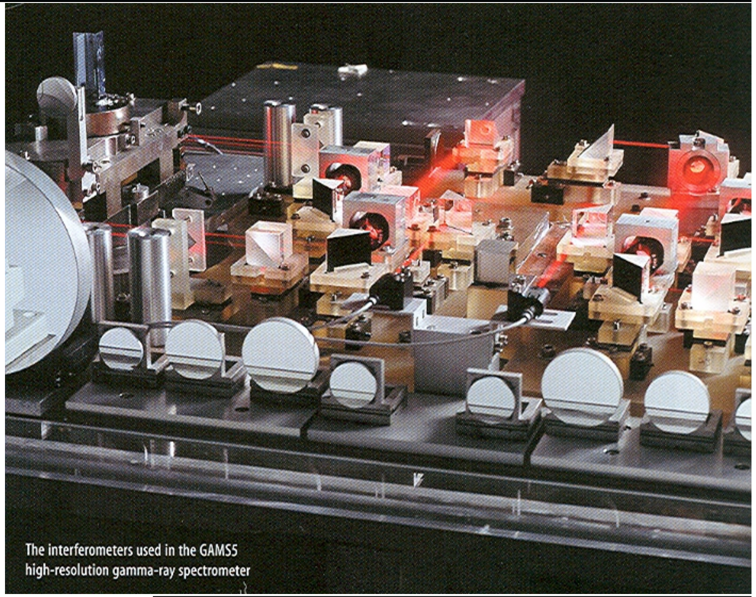

Measurement
Simulation
integral energy spectrum
for ^{124}Sn recoil ions
Counts
200000
150000
100000
50000
0
0
50
100
150
200
Retardation potential (V)

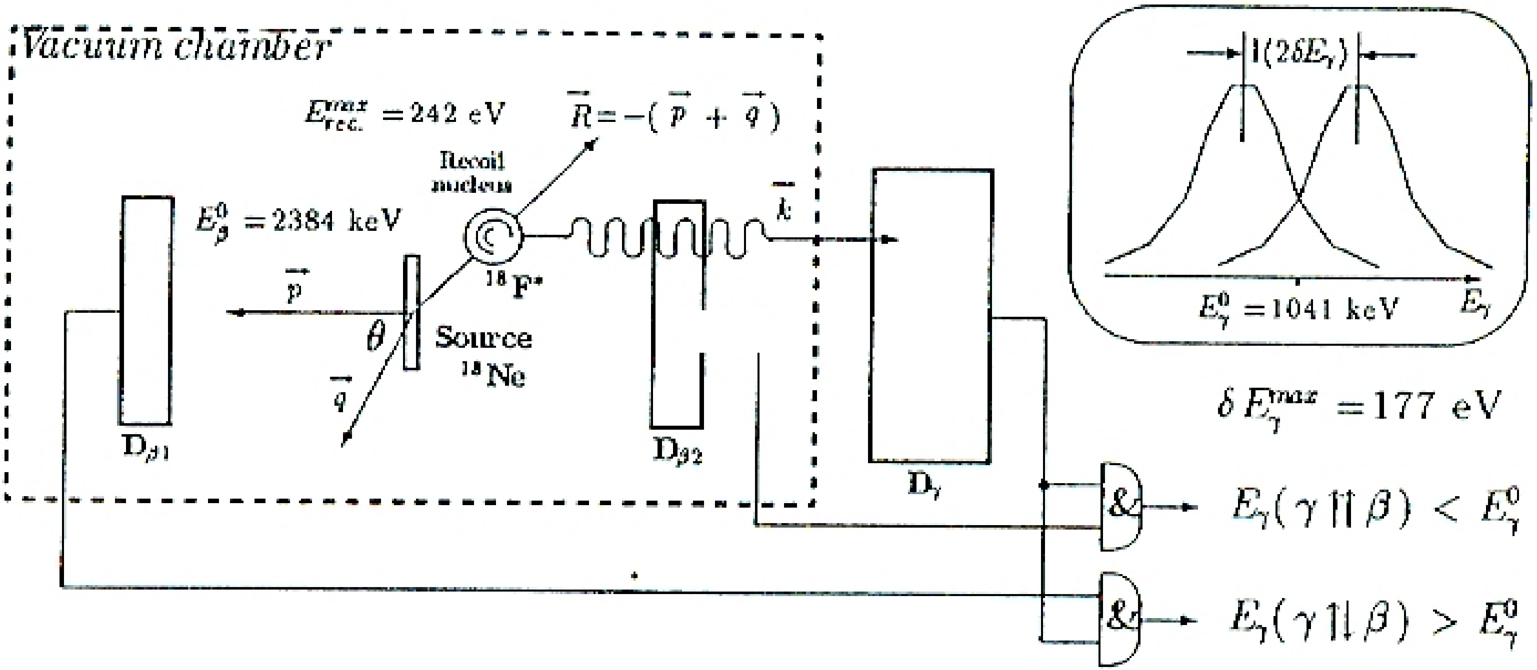

decay
trap
(20 cm)
cooler
trap
(20 cm)

βν-correlation from Doppler-shift of β-delayed γ-rays



V. Egorov et al., Nucl. Phys. A 621 91997) 745



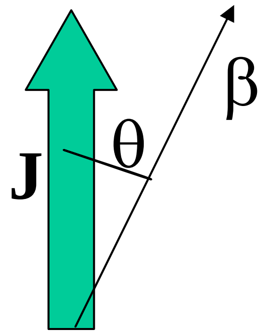


- momentum of recoil nucleus and therefore direction of ν momentum obtained from measured Doppler shift and beta particle momentum

- Doppler shift from precise measurement of γ-ray energy with a crystal spectrometer

2b. β asymmetry, *A*

$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{p}}{E_e} \tilde{A}$$



for a pure Gamow-Teller transition :

$$\tilde{A}_{GT}^{\beta^\mp} \cong \lambda_{J'J}\left[\mp 1 + \frac{\alpha Z m}{p} \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right) + \frac{\gamma m}{E_e} \mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right)\right]$$

$$\left[\gamma = \sqrt{1-(\alpha Z)^2}\right]$$

$-0.008 < \mathrm{Im}\,(C_T+C'_T)/C_A < 0.014$ (90% CL) from ^{8}Li @ PSI, R. Huber et al., PRL 90 (2003) 202301

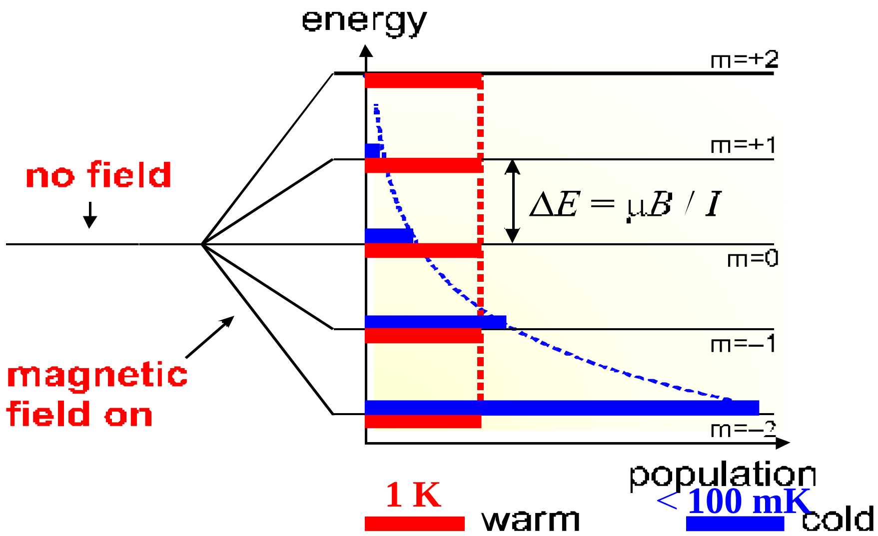
$\Delta A = 0.01 \rightarrow$ (for $\gamma m/E_e \cong 0.5$) Re [(C_T+C_T') / C_A] < 0.033 (90% CL)

(assuming maximal P-violation and T-invariance for V and A interactions)

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4} / A_{GT} independent of nuclear matrix elements

Low Temperature Nuclear Orientation + Geant 4

(K.U.Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)



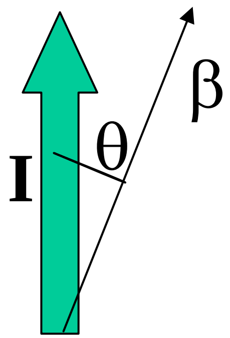
F. Wauters, I. Kraev, D. Zakoucky, N. Severijns et al.

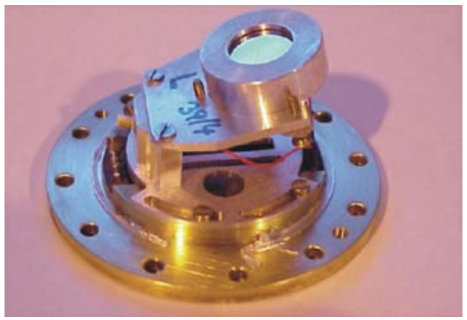
$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + \tilde{A}^{\beta^{\mp}}_{GT} \; P \; \frac{v}{c} Q \cos\theta$$

(polarization P from anisotropy of γ-rays) **Geant 4**

Leuven: ^{60}Co<u>Cu</u> , B_{ext} = 13 T

ISOLDE: ^{63}Cu<u>Fe</u> , B_{hf} = 22 T

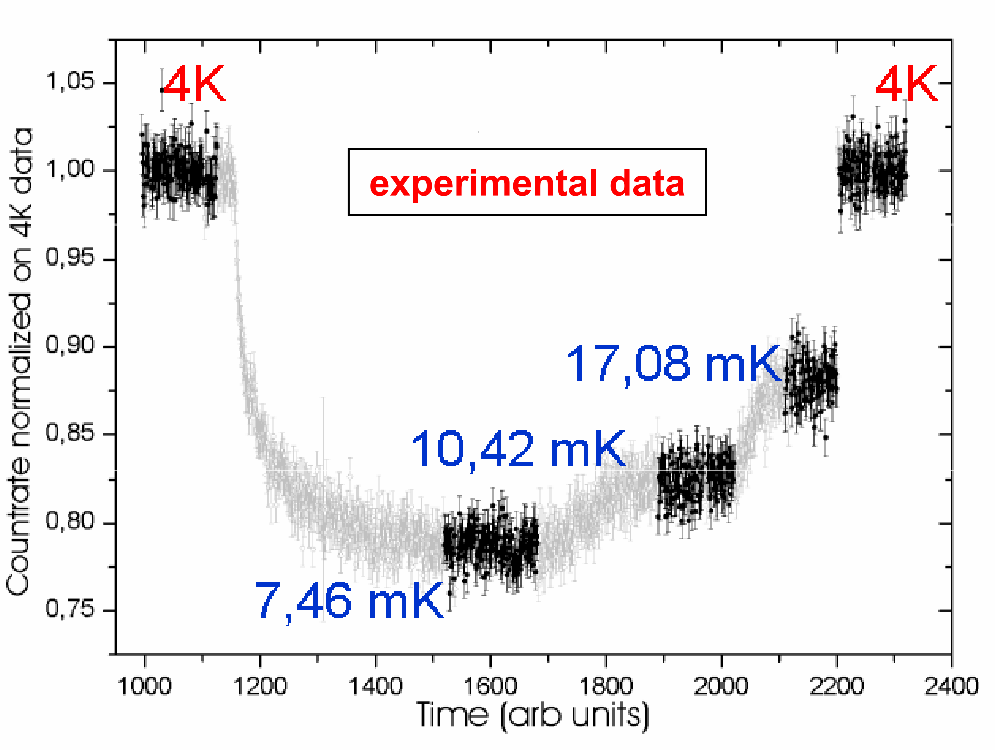


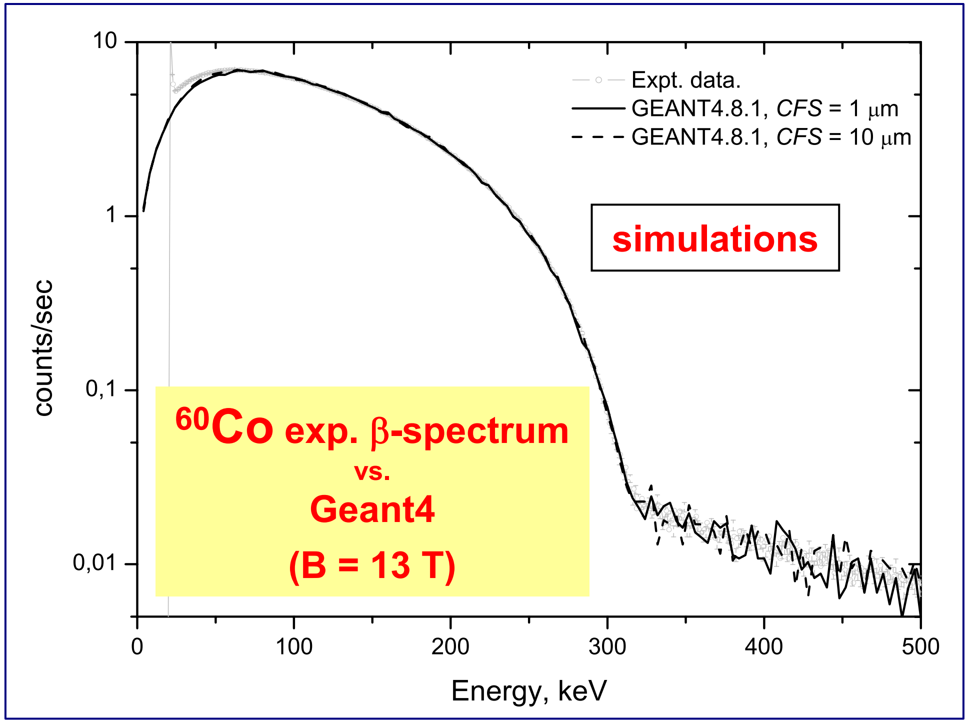


Analysis:

$$\frac{[\, W(\theta) - 1]_{exp}}{[\, W(\theta) - 1]_{sim}} = \frac{\left[\tilde{A}^{\beta^{m}}_{GT} \; P \; \frac{v}{c} Q \cos\theta \right]_{exp}}{\left[\tilde{A}^{\beta^{\mp}}_{GT,SM} \; P \; \frac{v}{c} Q \cos\theta \right]_{sim}} = \frac{\tilde{A}^{\beta^{\mp}}_{GT}}{\tilde{A}^{\beta^{\mp}}_{GT,\,SM}}$$

IS431-experiment





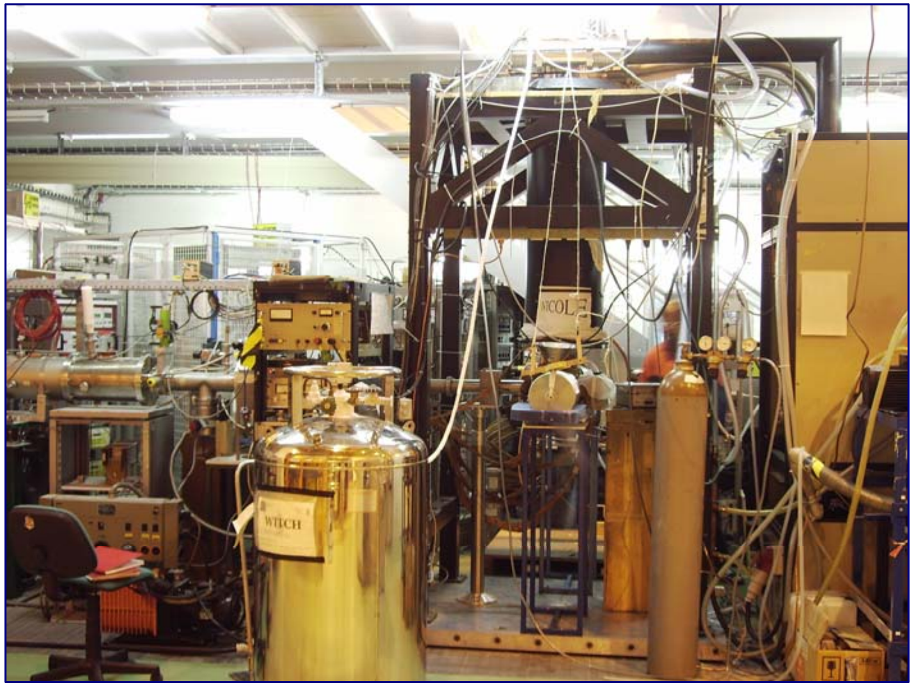
From ratio $\frac{[\ W(\theta)-1\ ]_{\mathrm{exp}}}{[\ W(\theta)-1\ ]_{\mathrm{Geant}}}$ get $\tilde{A}_{\mathrm{exp}} / \tilde{A}_{\mathrm{SM}}$

preliminary results :

$\tilde{A}_{\mathrm{exp}} / \tilde{A}_{\mathrm{SM}}$ = 1.021(12) for ^{60}Co

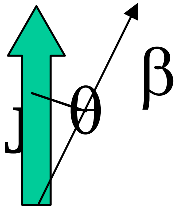
= 0.991(19) for ^{114}In

and data for ^{63}Cu under analysis



3. Symmetry tests - parity violation

3a. β asymmetry, *A*



$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{p}}{E_e} \tilde{A}$$

Manifest Left-Right Symmetric models

$W_1 = W_L \cos\zeta - W_R \sin\zeta$

$W_2 = W_L \sin\zeta + W_R \cos\zeta$

$\delta = m_1^2 / m_2^2$; $\zeta \cong 0.001$

for a pure Gamow-Teller transition :

$$\tilde{A}_{GT}^{\beta^\mp} \cong \mp \lambda_{J'J} \left[1 - 2(\delta + \varsigma)^2 \right]$$

(assuming T-invariance for V and A interactions, and no tensor component)

$\Delta A = 0.002 \rightarrow M(W_R) < 400\ \mathrm{GeV/c^2}$ (90% CL)

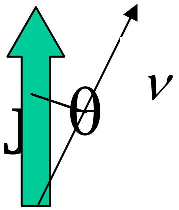
$\Delta A = 0.001 \rightarrow M(W_R) < 475\ \mathrm{GeV/c^2}$ (90% CL)

present 90% CL lower limit is $M(W_R) < 320\ \mathrm{GeV/c^2}$ (Severijns et al., NP A 629 (1998) 423c)

"probing the 500 GeV/c² region would provide new information on several extensions of the Standard Model "
(Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413)

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4} / A_{GT} independent of nuclear matrix elements

3b. ν asymmetry, *B*



$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{q}}{E_e} \tilde{B}$$

$$\tilde{B}_{GT}^{\beta^{\mp}} \cong \pm \lambda_{J'J} \left[1 - 2(\delta + \varsigma)^2 \right] = -\tilde{A}_{GT}^{\beta^{\mp}}$$

$$\frac{B^{\exp}}{B^{SM}}\left({}^{37}K\right) = 0.981 \pm 0.020(\text{stat}) \pm 0.013(\text{syst})$$

(in about 4 days of beam time ;

D. Melconian et al., Phys. Lett. B 649 (2007) 370)

can be reduced by factor of about 3 to 4 !

then to be reduced by factor of about 6 to 7
to be about equal to systematic error !

3. Symmetry tests - time reversal violation

- ***D* correlation :** $D \frac{\vec{J} \cdot (\vec{p}_e x \vec{p}_\nu)}{E_e E_\nu}$

  - sensitive to time reversal violating **V, A interactions**
  - only measured for **neutron** and for **^{19}Ne** till now (**always statistics limited** !)

D = -0.0004(6)
(several authors, 1958 - 2004)

D = 0.0001(6)
(F. Calaprice et al., 1969 - 1984)

- ***R* correlation :** $R \frac{\vec{J} \cdot (\vec{\sigma} x \vec{p}_e)}{E_e E_\nu}$

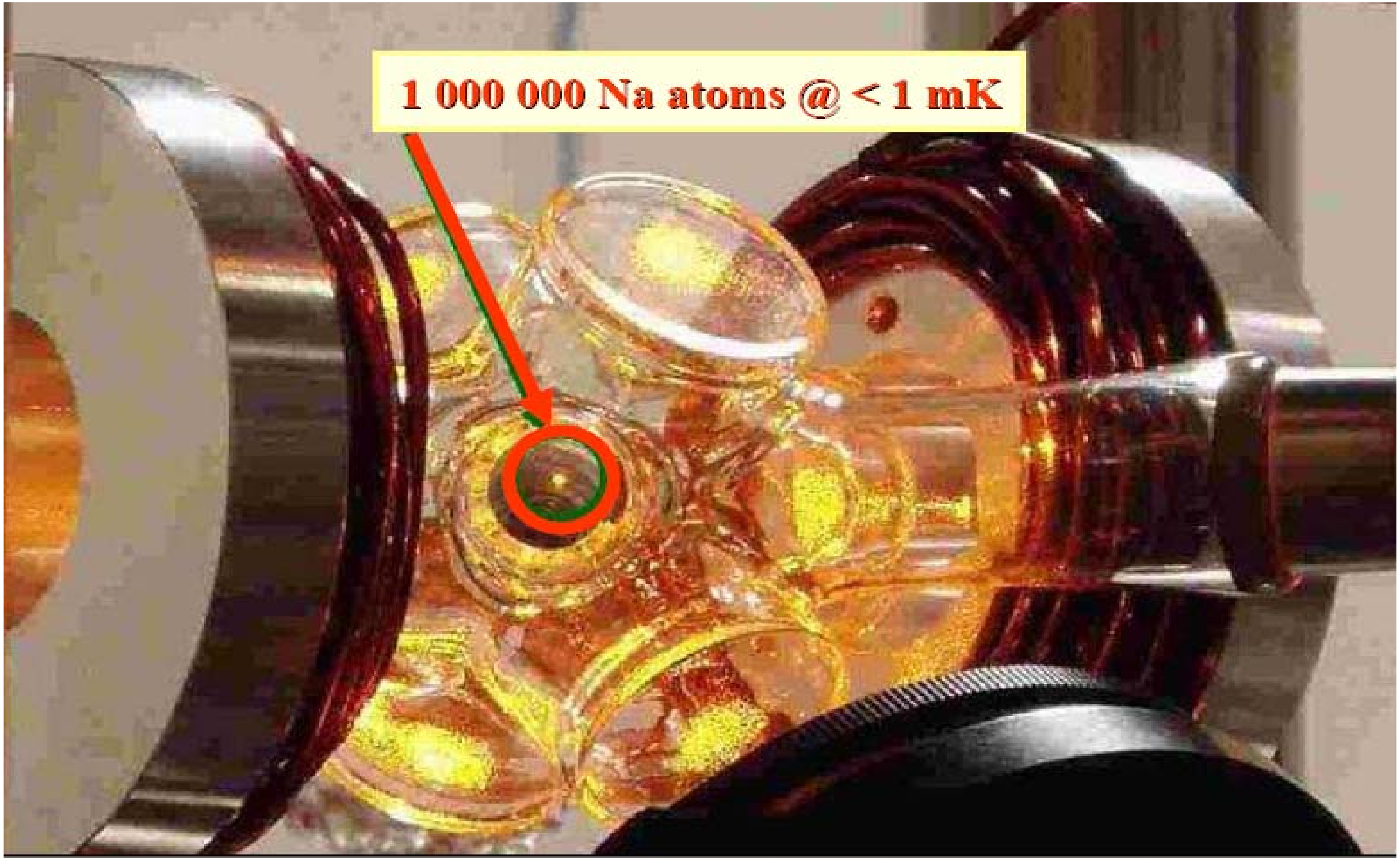
  - sensitive to time reversal violating **S, T interactions**
  - only measured for **neutron**, **^{8}Li** and **^{19}Ne** till now

R = 0.007(19)
(preliminary)
K. Bodek et al.,
to be published

R = 0.0009(22)
R. Huber et al.,
PRL 90 (2003) 202301

R = 0.079(53)
F. Schneider et al.,
PRL 51 (1983) 1239

In preparation: D(^{21}Na) in MOT optical trap at KVI-Groningen



4. Searches for heavy neutrinos

- recoil energy for nucleus that has emitted heavy neutrino is lower than for light one

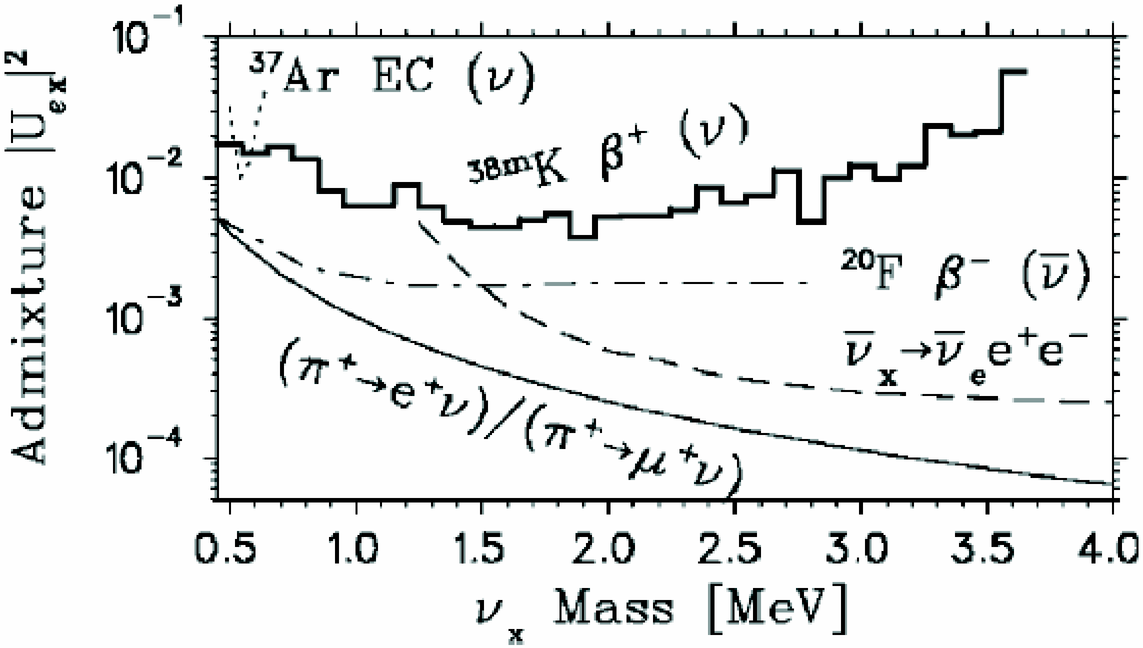
  → recoil ion energy in beta decay probes existence of heavy neutrinos that would mix (with amplitude U_{ex}) with light neutrino :

$$|\nu_e\rangle = \sqrt{1-|U_{ex}|^2}|\nu_0\rangle + U_{ex}|\nu_x\rangle$$

- current best result in nuclear beta decay

  from 38mK →

  (Trinczek et al., PRL 90 (2003) 012501)



- e.g. **heavy neutrino search with the WITCH spectrometer :**

decay : ^{144}Eu (10.2 s) → ^{144}Sm

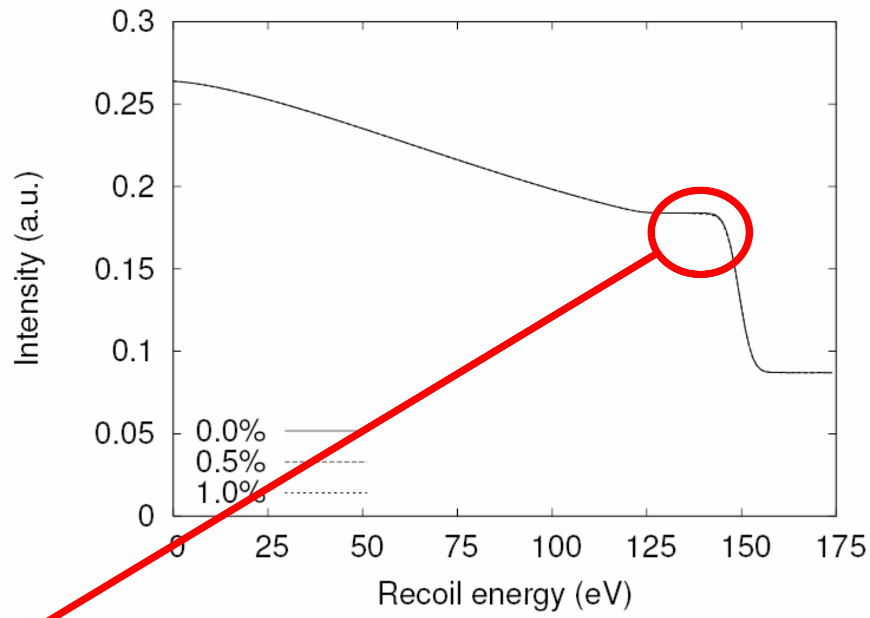
EC-branching : 9.7%

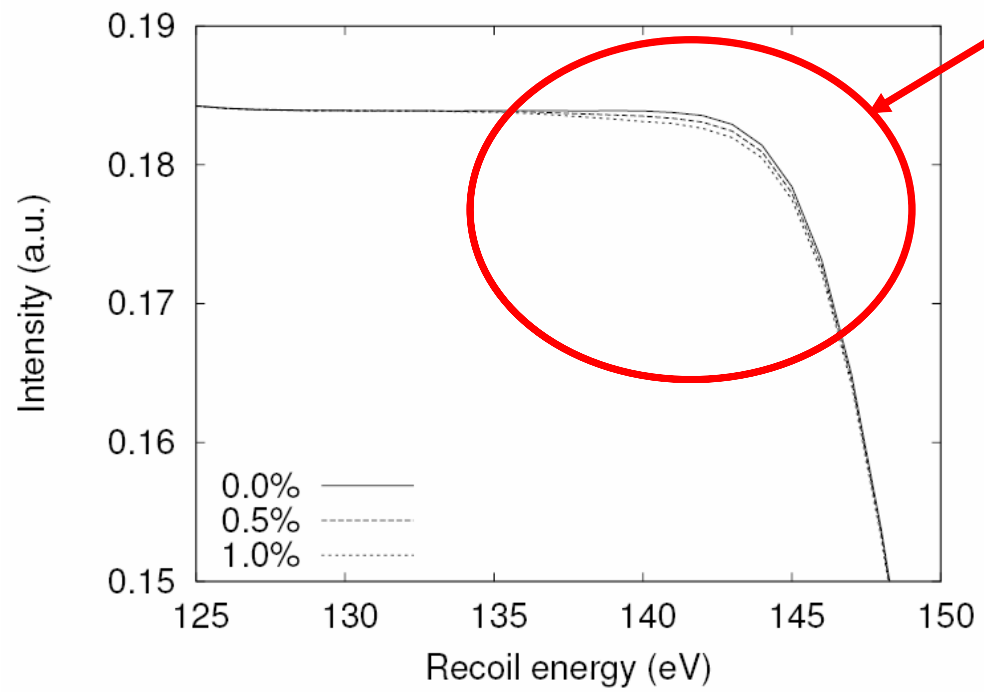
Q_{EC}-value : 6.3 MeV

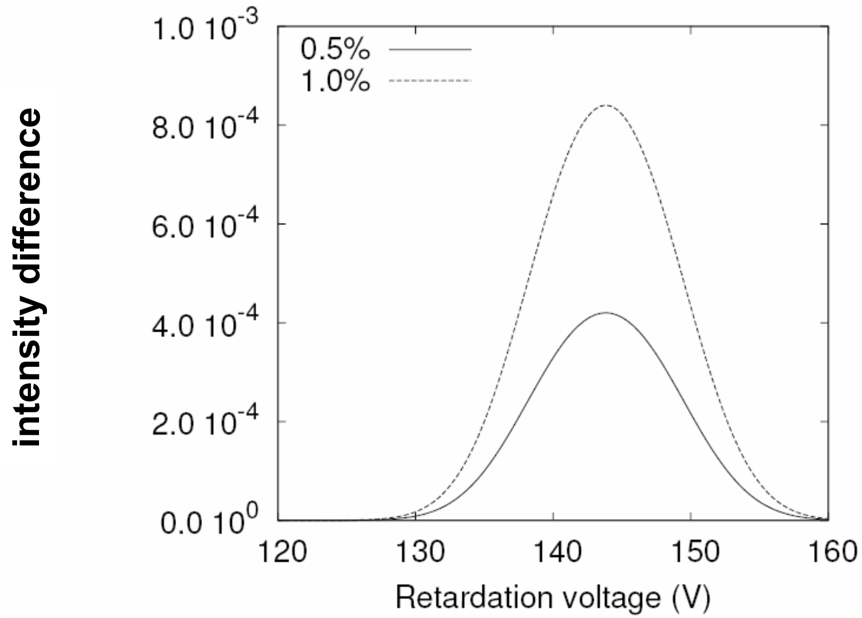
beta recoil endpoint : 125 eV

EC(m_ν = 0) recoil peak : 149 eV

& search for peak at e.g. 138 eV with 0.5% or 1% admixture







1. *ft*-values

→ **$0^+ \rightarrow 0^+$ transitions** (test CVC, unitarity test, right-handed currents, scalar currents, test nuclear structure corrections, …)

$T_{1/2}$ and BR for ^{18}Ne, ^{34}Ar, ^{38m}K and ^{74}Rb

2. searches for exotic weak currents (scalar and/or tensor currents)

→
- **atom traps (e.g. ^{21}Na, ^{37}K, ^{38m}K), Penning traps (e.g. ^{35}Ar), Paul traps (e.g. ^{6}He),**
- **beta asymmetry measurements (e.g. ^{19}Ne),**
- **but also Doppler-shift of gamma-rays (e.g. ^{18}Ne, ^{35}Ar) with a crystal spectrometer**

3. symmetry tests

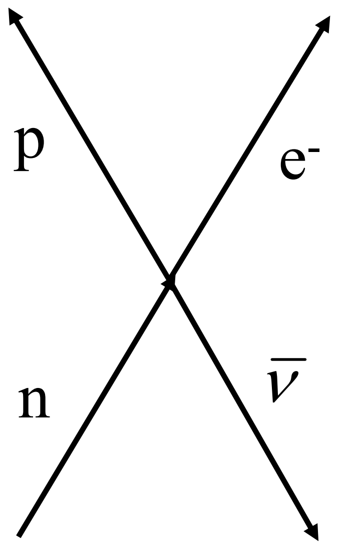
- **parity**
  - **beta asymmetry measurements (e.g. ^{18}Ne)**
  - **neutrino asymmetry in nuclear beta decay (e.g. ^{21}Na, ^{37}K)**
- **time reversal**
  - ***D* correlation ($J.p_e x p_\nu$; V,A) - (e.g. ^{19}Ne)**
  - ***R* correlation ($\sigma.J x p_e$; S,T) - (e.g. ^{8}Li, ^{19}Ne)**

4. searches for heavy neutrinos

<u>Motivation</u>:
- **long measuring times**
- **high precision**
- **good knowledge of apparatus required (systematc effects)**

STRUCTURE OF THE WEAK INTERACTION IN NUCLEAR BETA DECAY

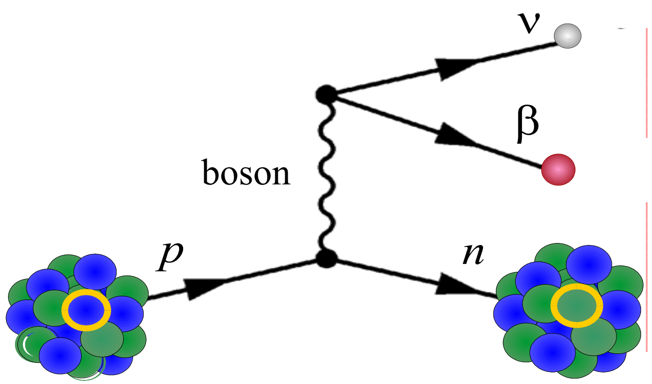
β-decay Hamiltonian (Lee & Yang) :



$$H_\beta/g \propto (\bar{p}\, 1\, n)\,[\bar{e}\; 1\; (C_S + C_S'\gamma_5)\,\nu\,]$$
$$+ (\bar{p}\,\gamma_\mu\, n)\,[\bar{e}\;\gamma_\mu\,(C_V + C_V'\gamma_5)\,\nu\,]$$
$$+ \frac{1}{2}(\bar{p}\,\sigma_{\mu\nu}\, n)\,[\bar{e}\;\sigma_{\mu\nu}\,(C_T + C_T'\gamma_5)\,\nu\,]$$
$$- (\bar{p}\,\gamma_\mu\gamma_5\, n)\,[\bar{e}\;\gamma_\mu\gamma_5\,(C_A + C_A'\gamma_5)\,\nu\,]$$
$$+ \underbrace{(\bar{p}\,\gamma_5\, n)}_{\approx 0}\,[\bar{e}\;\gamma_5\,(C_P + C_P'\gamma_5)\,\nu\,]$$

with γ_i $(i = 1, 2, 3, 4)$ Dirac matrices $(\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4)$

and $\sigma_{\mu\nu} = -\frac{i}{2}(\gamma_\mu\gamma_\lambda - \gamma_\lambda\gamma_\mu)$



P-violation if $C_i \neq 0$ and $C_i' \neq 0$

T-violation if $\mathrm{Im}(C_i^{(')}/C_j) \neq 0$

the Standard Model and beyond:

* $C_V = 1$ (CVC)
* $C_A = -1.27$ ($g_A/g_V = -1.2699(7)$ from n-decay)
* $C_V' = C_V$ & $C_A' = C_A$ (maximal P-violation)

* $C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0$ (only V- and A-currents)

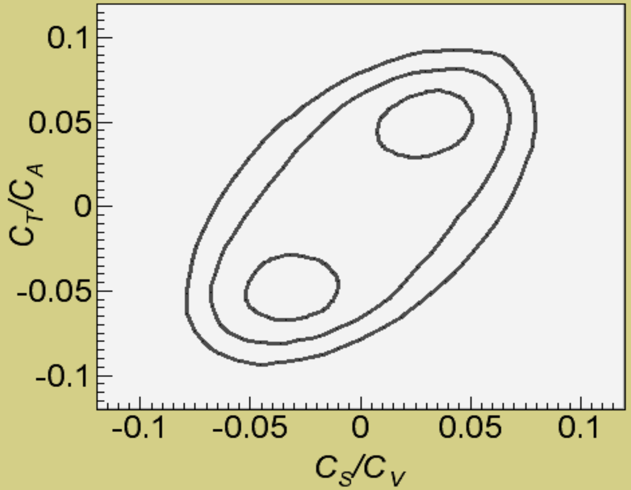
experimental upper limits:

(neutron and nuclear β-decay)

$$\left| C_T^{(\,'\,)} / C_A \right| < 0.09$$

$$\left| C_S^{(\,'\,)} / C_V \right| < 0.07 \qquad (95\%\,\mathrm{CL})$$

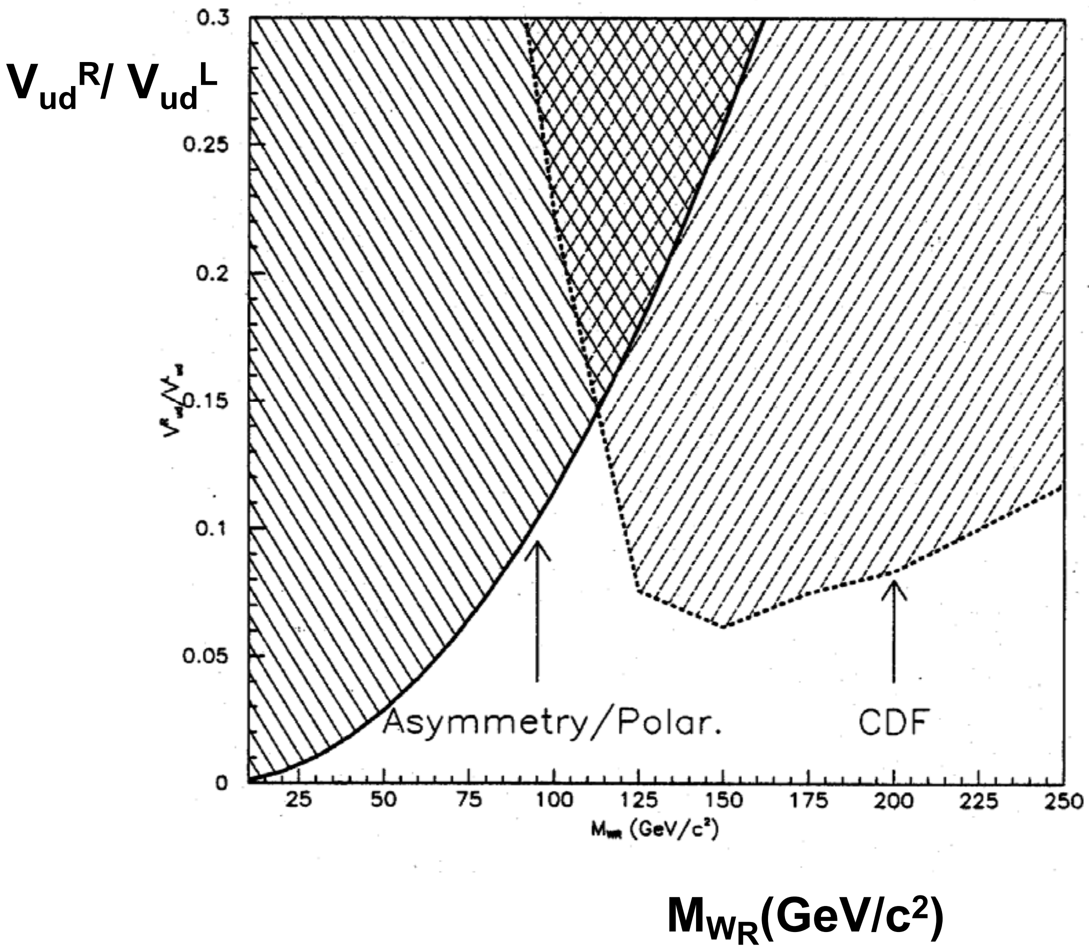
for right-handed exotic couplings

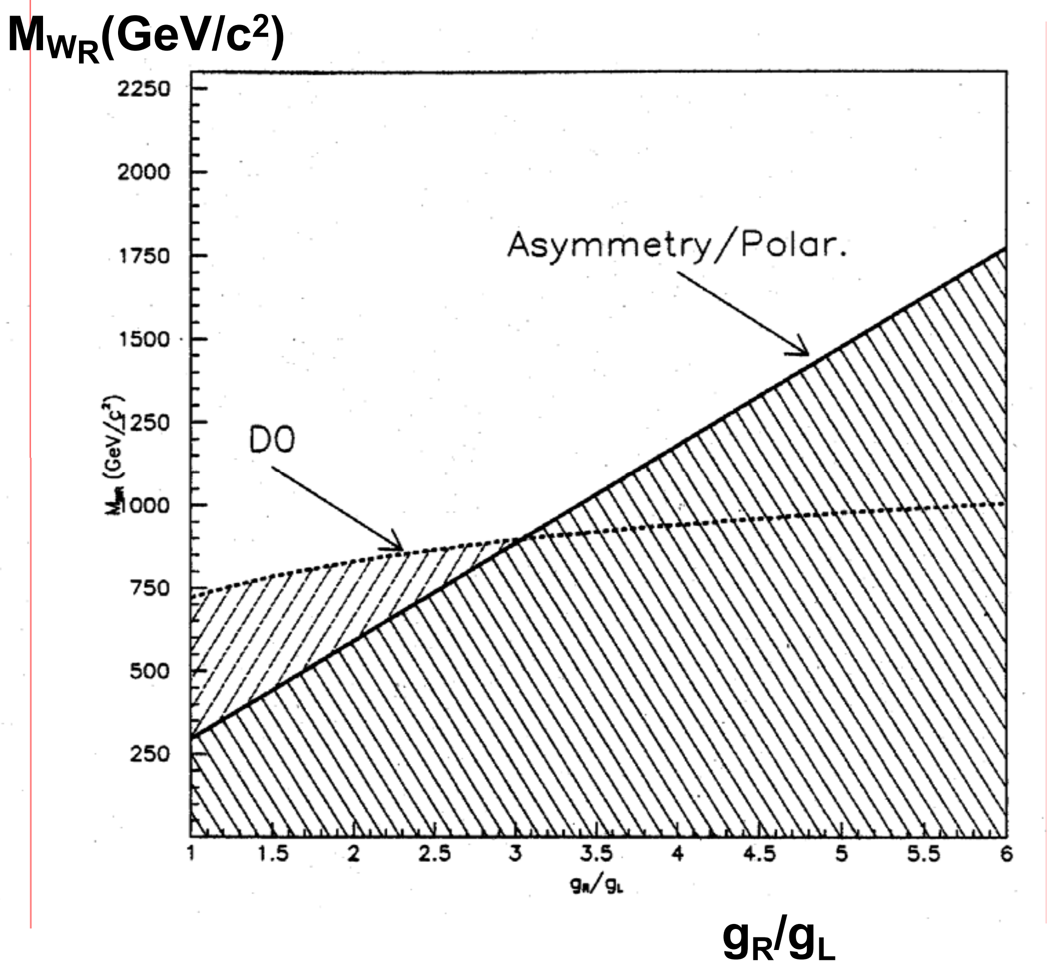


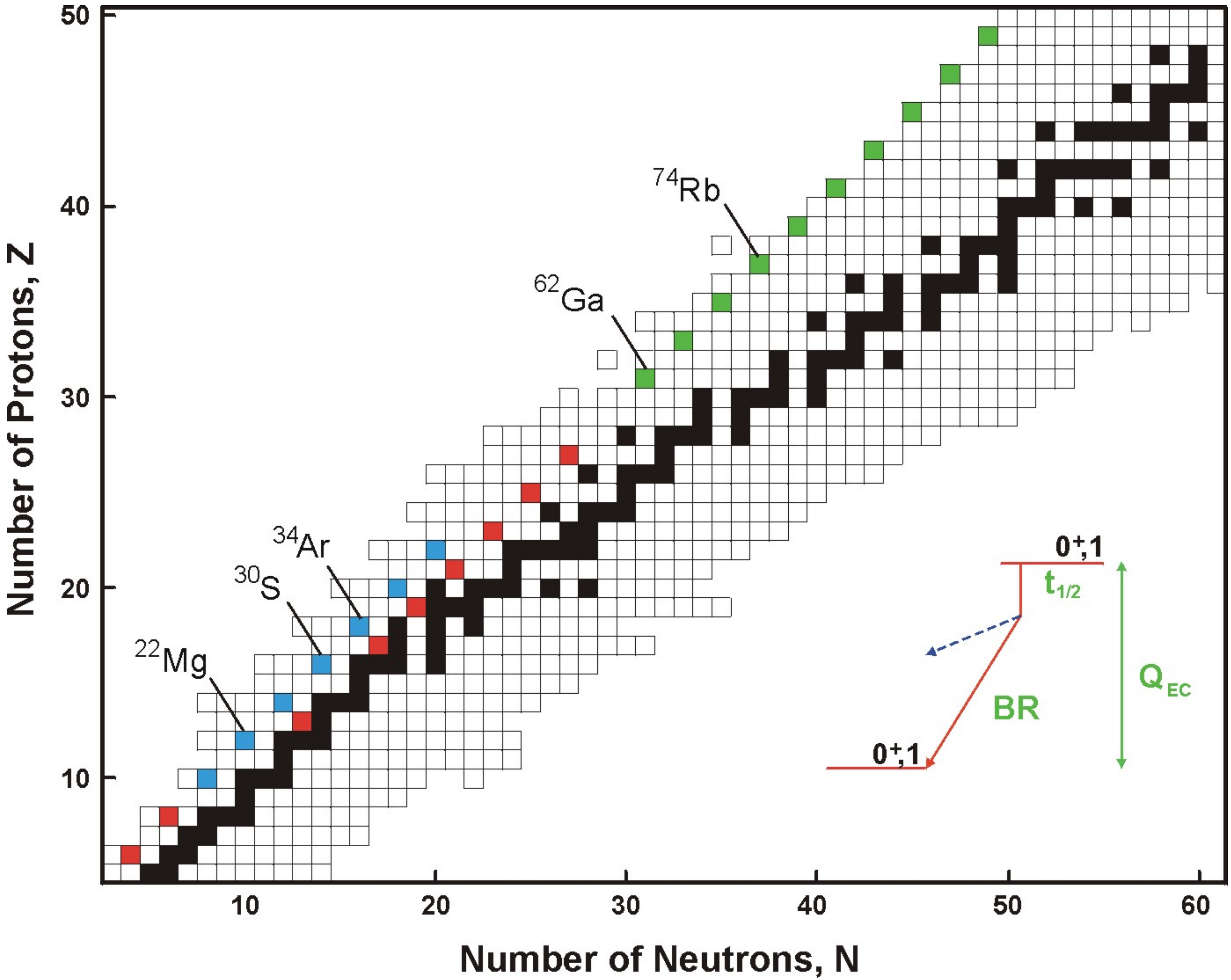
from: N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991

* **no time reversal violation**
(apart from the small CP-violation described by the phase in the CKM matrix)

Comparison of beta decay rhc results with collider results, assuming general LRS models

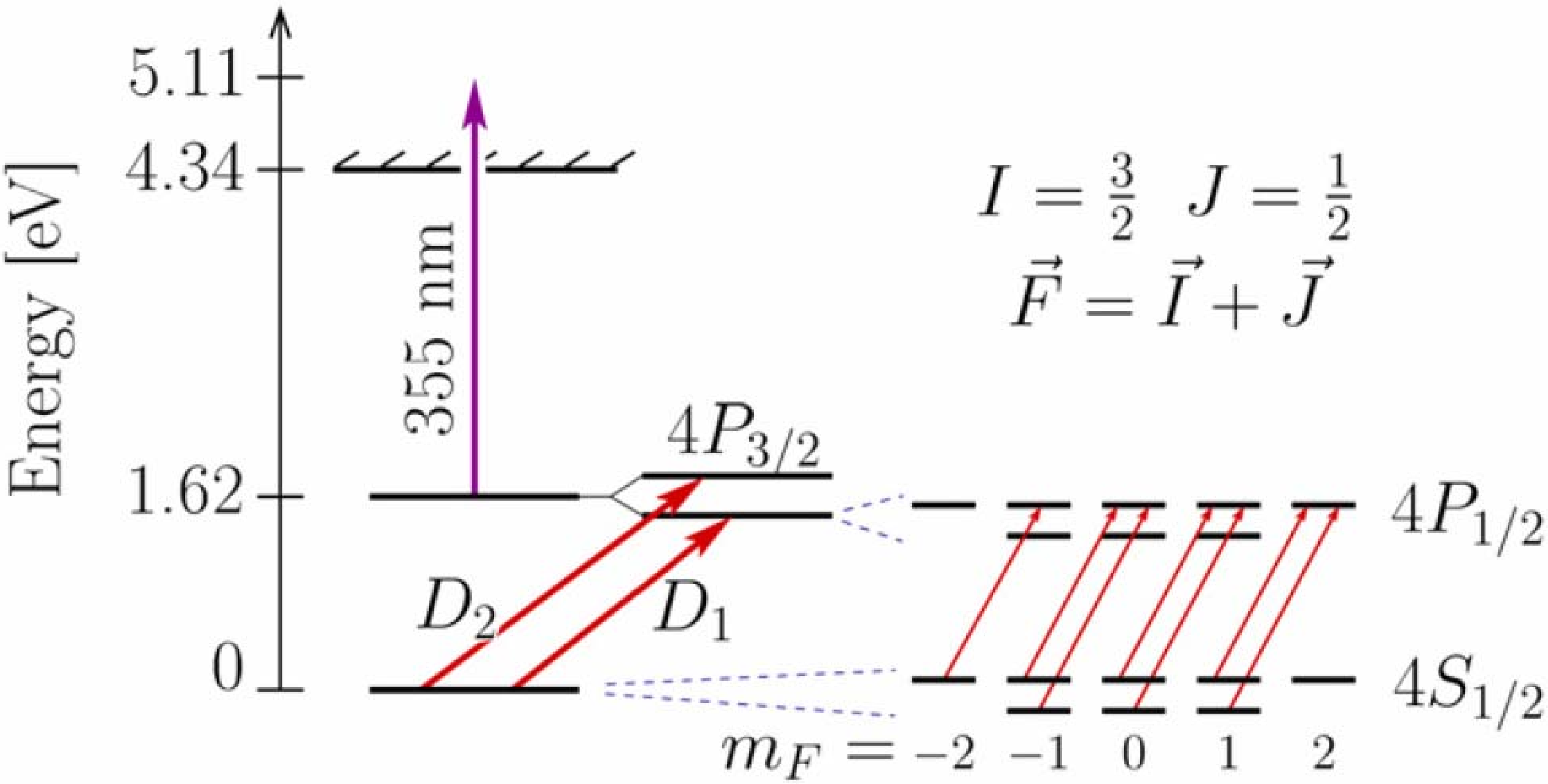


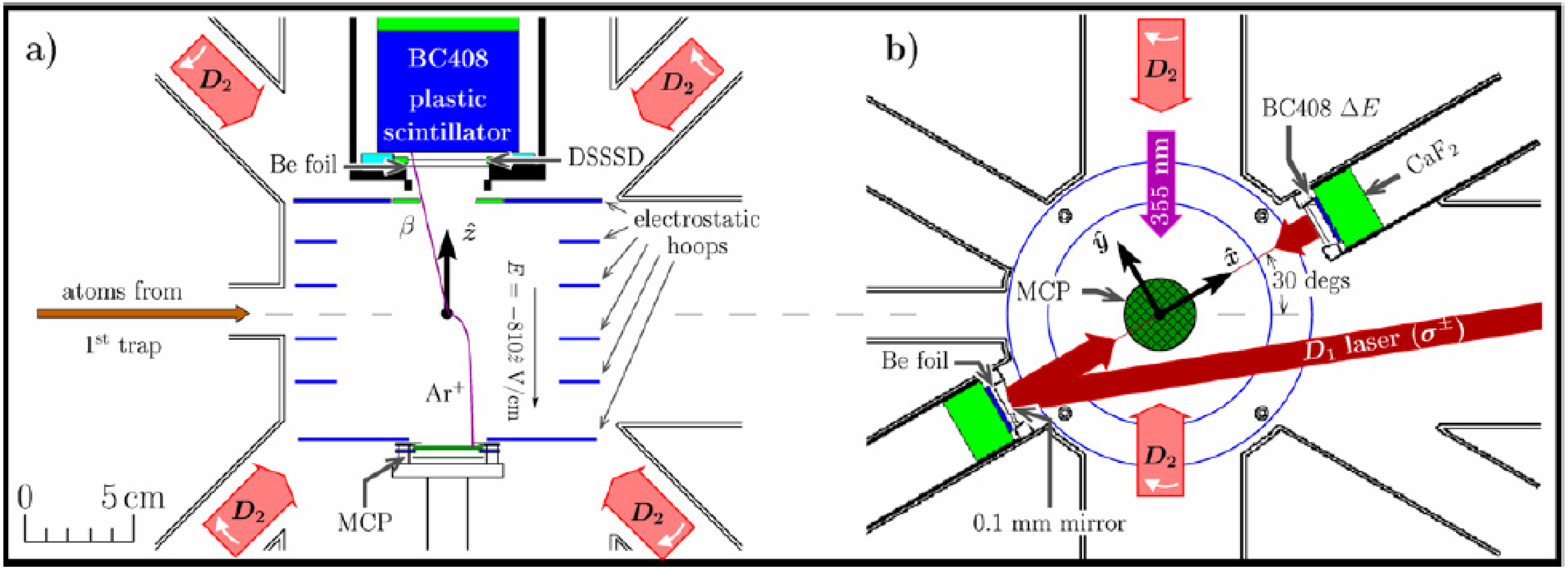




Number of Protons, Z
Number of Neutrons, N
10
20
30
40
50
60
74Rb
62Ga
34Ar
30S
22Mg
0+,1
t1/2
QEC
BR
0+,1

(J.C. Hardy)


Energy [eV]
5.11
4.34
1.62
0
355 nm
$I = \frac{3}{2}$ $J = \frac{1}{2}$
$\vec{F} = \vec{I} + \vec{J}$
$4P_{3/2}$
$4P_{1/2}$
D_2
D_1
$4S_{1/2}$
$m_F = -2$ -1 0 1 2



a)
BC408
plastic
scintillator
Be foil
DSSSD
electrostatic
hoops
β
ẑ
atoms from
1st trap
Ar+
E = −810ẑ V/cm
D2
0
5 cm
MCP
b)
D2
355 nm
BC408 ΔE
CaF2
ŷ
x̂
MCP
30 degs
D1 laser (σ±)
Be foil
0.1 mm mirror

Princeton D(^{19}Ne) experiment

- **polarized ^{19}Ne from Stern-Gerlach magnet**
- $\langle \vec{p}_e + \vec{p}_\nu + \vec{p}_R \rangle = 0$ **for atoms in the cell** → $\vec{J} \cdot (\vec{p}_e \text{x} \vec{p}_\nu)$ is equivalent to $-\vec{J} \cdot (\vec{p}_e \text{x} \vec{p}_R)$
- **E(^{19}F$^-$) < 200 eV**

result: D = +0.0004(8)

F. Calaprice et al., 1969 - 1984

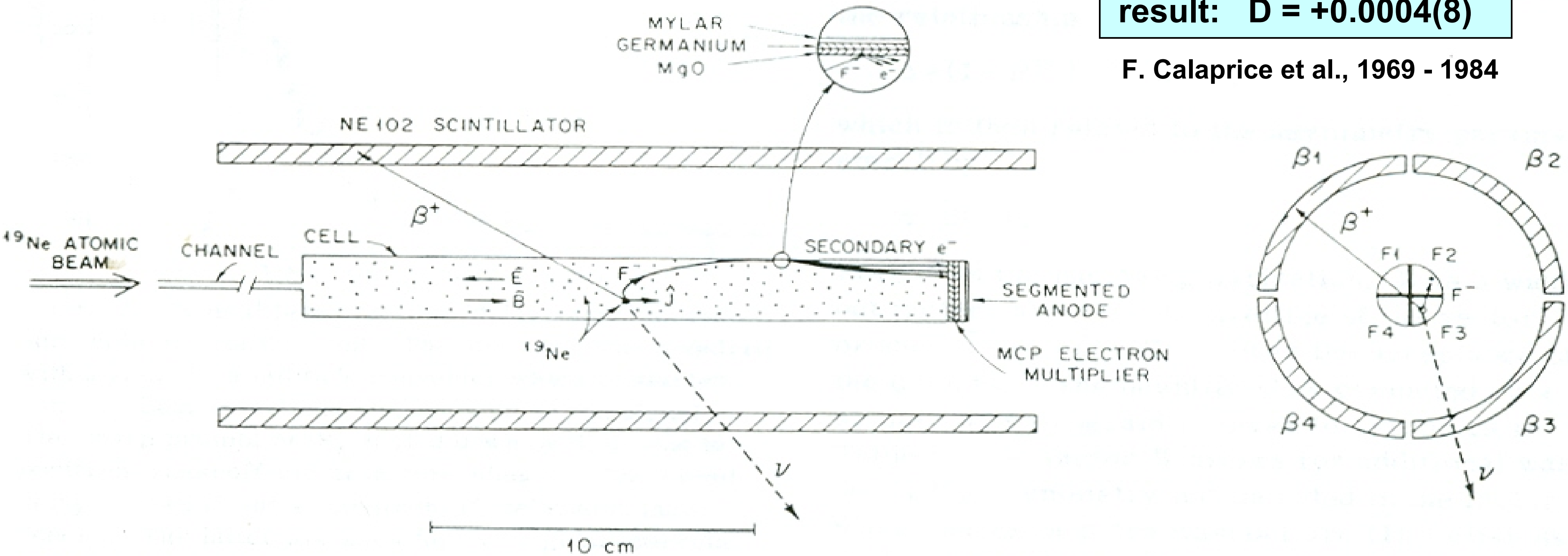
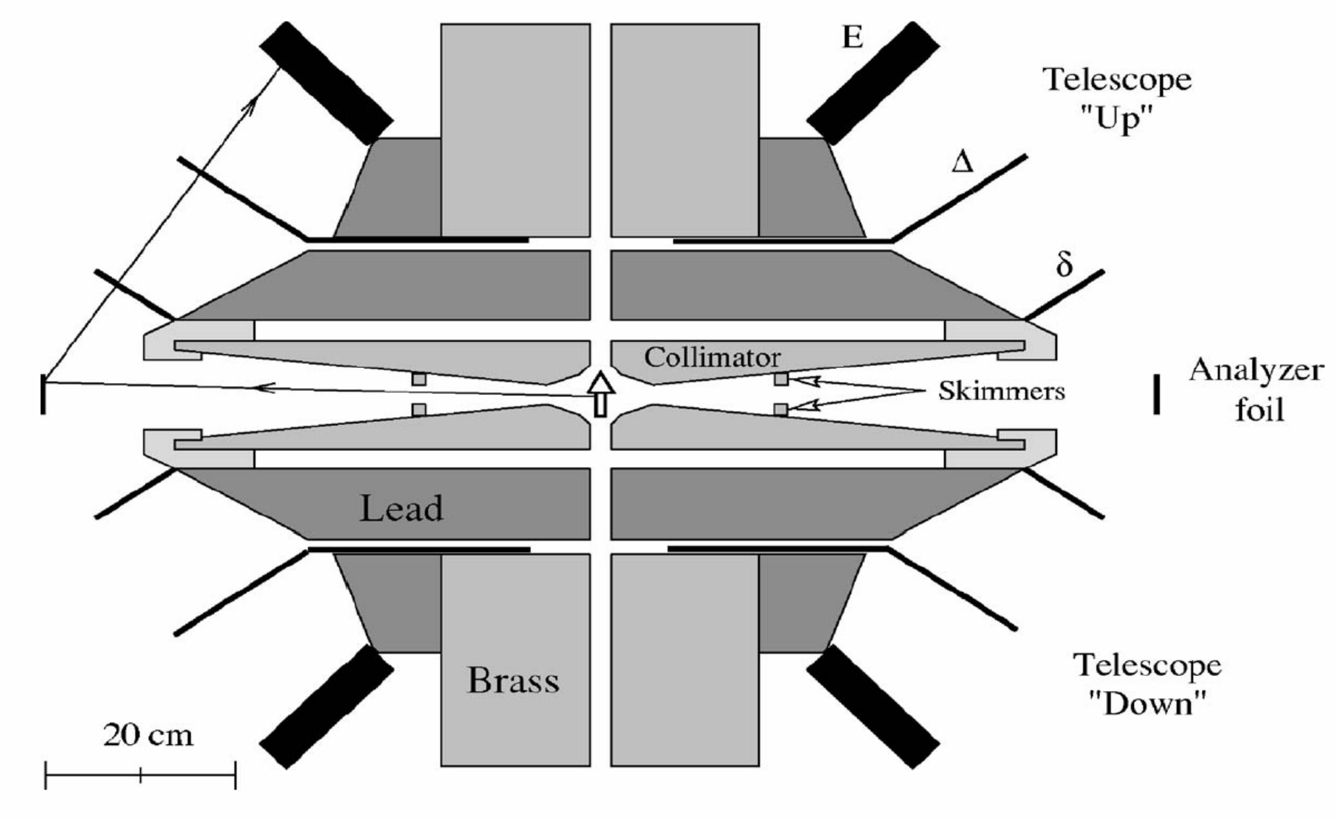
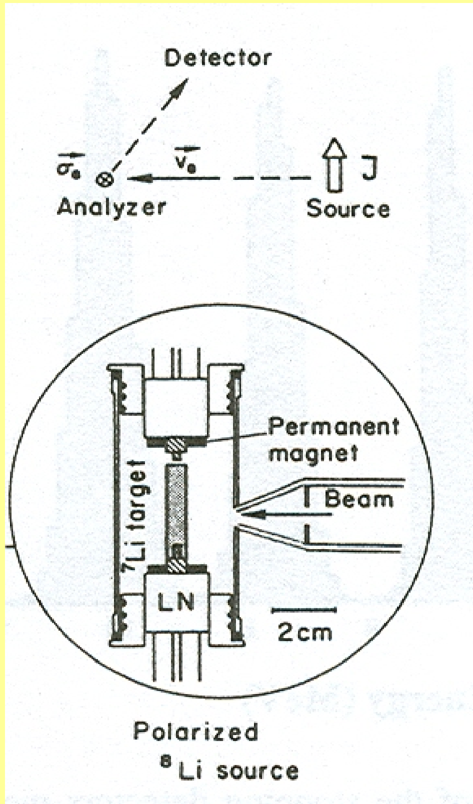


FIG. 1. Schematic illustration of the cylindrical cell and the detector system. Polarized ^{19}Ne, which enters the cell through a long narrow channel, fills the entire cell (dots). A uniform magnetic field maintains the polarization along the cell axis. In a typical decay the positron passes through the thin wall of the cell to one of four plastic scintillators (β_1 through β_4). The F$^-$ recoil ion is accelerated along the cell axis by an electric field. The ion strikes the inside surface emitting secondary electrons which are accelerated into an electron multiplier segmented in four parts (F_1 through F_4).

experimental set-up and result - ^{8}Li





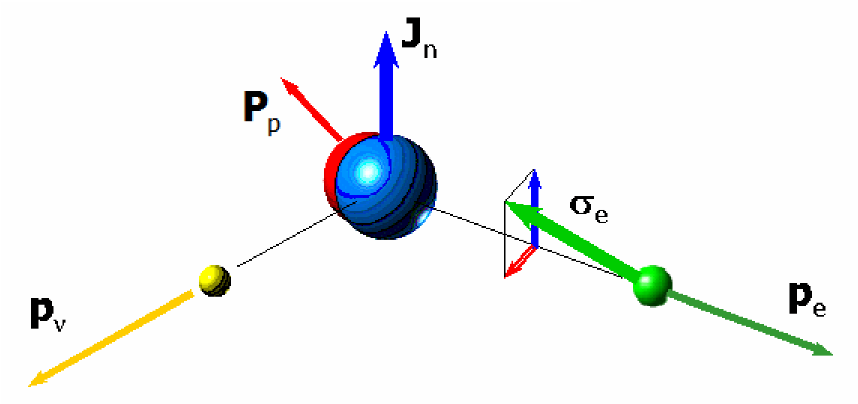
R. Huber et al., PRL 90 (2003) 202301

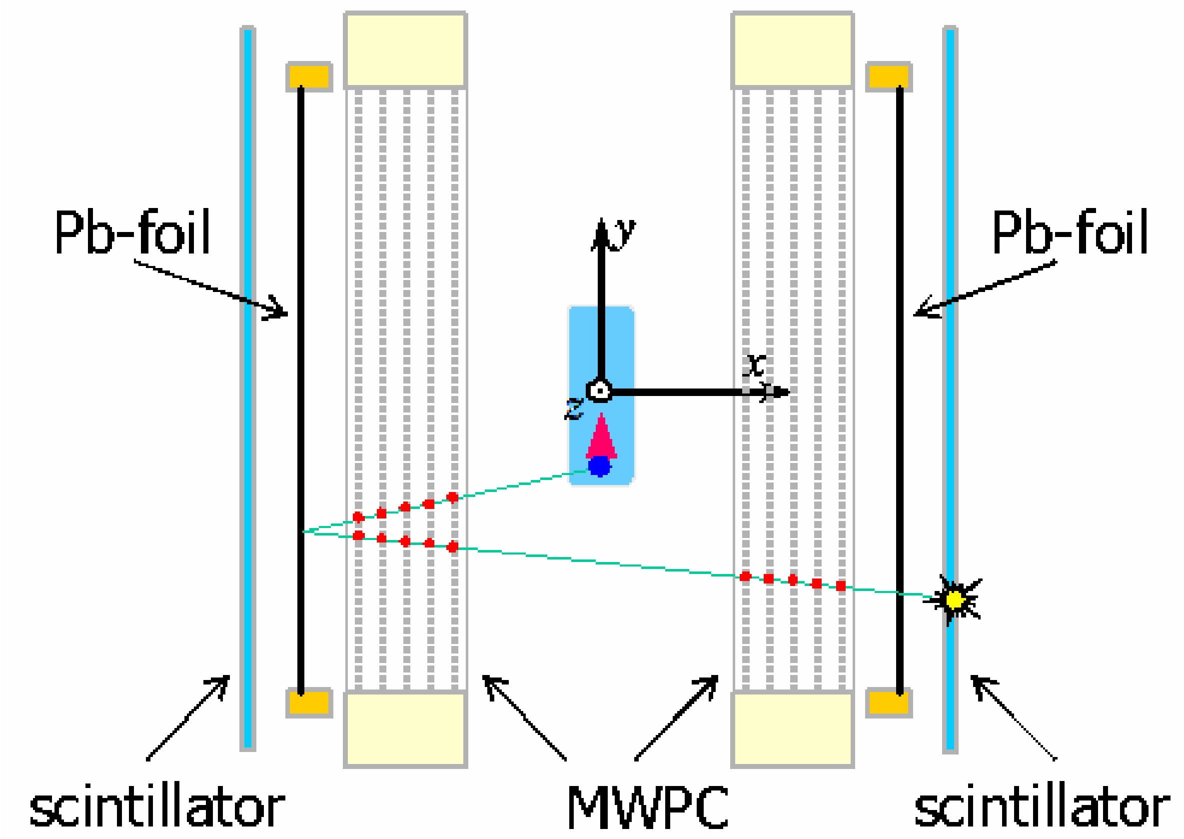
3. Testing time reversal violation in free neutron decay

(Univ. Krakow, PSI, LPC-Caen, K.U.Leuven, …)

(SINQ-FUNSPIN)

$$R\,\frac{\vec{J}\cdot(\vec{p}\times\vec{\sigma})}{E}$$





$$R = 0.28\ \mathrm{Im}\left(\frac{C_S + C_S'}{C_A}\right) + 0.33\ \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right)$$

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